Wingship Investigation

VOLUME 1

Final Report

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13. ABSTRACT *(Maximum 200 words)*

The Advanced Research Projects Agency (ARPA) has completed an investigation of Wingship concepts and technologies to examine their relevance and utility in future defense applications. A select team of technical experts from U.S. Government and industry was formed by ARPA to assess Wingship-related technologies and mission applications. The diverse group was comprised of Western experts in Wingship-unique and related technologies, including flight controls, aerodynamics, hydrodynamics, propulsion, and advanced structures. Transportation specialists and other mission analysts also participated. The Wingship Investigation concluded that vehicles approaching the efficiency and capacity required for strategic heavy lift are about 10 times larger (in gross weight) than any existing Wingship or other flying water-based craft, and about five-times larger than most experienced Russian or American experts recommend building using current technology. The study concluded that, while the cost and technical risks of developing these very large Wingships are currently unacceptable, there may be some promising military applications for Wingships in the 400- to 1000-ton range. Experience with these relatively smaller vehicles could also permit a growth path for the technology.

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Col. Michael S. Francis USAF, ARPA Program Manager, organized this investigation. He selected many of the participants, interfaced with Congress and provided executive level direction during its course.

Several authors cooperated to write this report. Writing assignments were issued by topic and section. The team of writers deliberately included talented people with different backgrounds. Inevitably, there were differences in writing style and emphasis among the various writers. Also, the writers had different experiences during the investigation. For example, not all writers visited Russia. There was a fair amount of communication and cross reading between writers. And, in the final event, a smaller team edited the whole document to fill in transitions, remove contradictions, and make the style a little more uniform. Consequently, the material in each section is not exclusively attributable to a single individual. The following paragraphs, in alphabetical order by author name, describe each author's contribution.

Eugene Covert wrote the expository section on the relationships and differences between technology and concept demonstrators. His insight was key in sorting out some of the rationale of the Russian programs.

Jim Camp wrote material on the history of the Russian development programs.

Dieter Czimmek wrote the initial material on structures. Burt Rutan provided structures information. Mr. Czimmek also provided some critical information on rogue waves and their detection and avoidance. At the time of his contributions, Dieter Czimmek was a senior technical staff member at the Newport News Shipyard responsible for high speed vehicle structures.

Roger Gallington suggested initial document outlines, and wrote various transition sections such as introductions, summaries, and results. He used comments of several outside reviewers to edit the report. He wrote some of the material on PAR.

Joseph Gera wrote the material on stability and control. He also made contributions to the aerodynamics section and served as a critical reviewer.

Eric Lister wrote all the propulsion material. He relentlessly sought out propulsion related issues and solutions. Eric courageously produced the earliest draft of his sections and served as a pathfinder for others.

Len Malthan computed the parametric results and wrote them up for this report. These early results were key for the mission analysis team to get an idea of what kind of performance they could expect from vehicles similar to the Russian LUN but of different sizes and proportions and with improvements in propulsion and structures technology.

Balusu Rao researched the major characteristics of a wide class of seaplanes and WIGs. He also made estimates of the propulsion performance improvements that might result from designing engines specifically for the wingship application.

John Reeves wrote the aerodynamics sections. He took particular care to compare the various analytical methods of predicting the benefit of ground effect. John also wrote the appended sections on seaplane and landplane performance. Mr. Reeves received assistance from Stephan Hooker and Hal Fluk.

Daniel Savitsky wrote the hydrodynamics sections. He paid particular attention to correlating empirical relations used for estimation in design to similar relations used in Russia and found substantial agreement.

C.F. Snyder coordinated the mission analysis and wrote that section with major contributions from Frank Macauley of BDM Federal and Sam Finch of Lockheed Aeronautical System Company. He also wrote sections of the Operational Issues. Mr. Snyder was at the forefront in establishing relations with the Russian team to foster the exchange of mission information.

Stephan Hooker wrote a minority report on the performance characteristics of a large-scale Wingship. This report is included in Appendix M.

Appendix I contains the resumes of authors, and other members of the investigating team.

1. Executive Summary

A wingship is a sea-based flying vehicle that exploits efficiency-enhancing ground effect by flying most of its design mission close to the surface of the sea. The most recent large Russian designs resemble stubby winged seaplanes. Congress directed the Advanced Research Projects Agency (ARPA) to investigate the wingship vehicle concept and directed the Department of Defense (DoD) to report back on whether it had a validated military requirement for such a vehicle. This report is the result of ARPA's investigation.

To conduct the investigation, ARPA formed a team of technologists and mission analysts. Some of this team traveled to Russia for extensive fact finding. Some of the team witnessed a US funded demonstration flight of a Russian wingship on the Caspian Sea. Some of the team did a parametric analysis of Russian-style wingships to estimate their optimum performance and performed technical audits of a 5000 ton wingship concept. During the course of the investigation, there were numerous meetings for information exchange. The investigation offered funded opportunities for US and Russian technical communities to address some of the most troublesome problems. The US technical community was responsive. Russia was not.

The investigation found that: (1) By far, the largest wingship programs have been Russian; (2) There have been no operational deployments; (3) A Russian wingship lifted the greatest weight ever from the water; (4) Russian programs focused on tactical military missions -- not the strategic supply mission, which was the initial US emphasis; and (5) Several efficiency-reducing wingship features detract substantially from the efficiency gains resulting from flight very near the sea.

The investigation concluded that: (1) several military missions which emphasize the speed and persistence of a wingship are promising; (2) wingships approaching the efficiency and capacity required for strategic mobility are ten times the gross weight of the largest wingship to date and five times the gross weight that any experienced US or Russian design team would suggest; (3) based on their evolution to date, and within the bounds of current and forseeable projected technology and projected life cycle cost, wingships do not appear promising for the long range strategic lift mission in the forseeable future; and (4) western technology and modern Russian technology could improve the performance of Russian-style wingships.

The ARPA Programs Managers team recommends: (1) Complete the mission and utility analysis emphasizing military missions which exploit the wingship speed and persistence; (2) Design a

wingship to perform the most promising of the military missions to obtain a better estimate of utility, cost, and related technical uncertainties; (3) implement of a technology development program to address key technical issues associated with the wingship concept; and (4) Complete the ongoing analysis and initiate suggested experiments addressing the most important technical problems, such as the large power required for takeoff, found during this investigation.

2. Introduction

This introductory section describes the background and purpose of this evaluation, defines the wingship, describes a vision of its performance and utility, and describes the content of the rest of the report.

2.1 Background And Purpose Of The Evaluation

This report summarizes the results of an Advanced Research Projects Agency (ARPA) evaluation of wingship technologies and concepts in response to Congressional direction (Figure 2.1-1) to accomplish "experimental planning and related studies in association with wing-in-ground effect vehicles." This study specifically supports a requirement for the Secretary of Defense to report back to Congress on whether or not there is a validated military requirement for such vehicles in projected defense missions.

To satisfy the Congressional tasking, ARPA crafted a program to accomplish the following objectives.

1. Evaluate technologies and concepts applicable to wingship type surface effect vehicles to determine the development feasibility, risk, performance potential and limitations associated with these vehicles. This evaluation should include technologies developed by the former Soviet Union.

2. Plan experiments and studies to verify and/or validate these assessments.

3. Assess the mission utility of these vehicle types in satisfying defense requirements (Congressional approval was given in late July 1993)

4. If outcome of the studies warrant, conduct experiments and studies designed to further assess and/or develop wingship technologies and concepts.

This report and subsequent "briefing", along with final results, will be presented to the Secretary of Defense to assist in his evaluation of wingship requirements and to support his report(s) to Congress on this issue.

Congressional Direction

Original Language - October 1992

The conferees direct that, from within the total amount of funds appropriated for this program element, $5,000,000 is available only for the Wingship project... The conferees direct that in providing funds... the Defense Advanced Research Projects Agency shall not decrement any other activities to which Congress has added funds or which have been designated as items of special Congressional interest.

The funds to be made available for the Wingship project may only be used for experimental planning and may not be used to enter into any contractual arrangement which would commit the government to proceed beyond the planning stage. No later than May 1, 1993, the Secretary of Defense is directed to report to the Congressional defense committees whether there is a validated military requirement for a wingship and how any need for such a system relates to other programs to improve U.S. airlift and sealift capabilities. This report also should contain a clear statement of policy whether the Defense Department would want to pursue a wingship program.

Modified Language - July 1993

ARPA may use funds for technical evaluation, utility analysis, and evaluation of technologies developed by the former Soviet Union.

Funds Released to Project: $2.0M - February 1993 & $3.0M - July 1993

Figure 2.1-1 Congressional Direction

Because of their unique and extensive involvement in the development of large wingships over the last three decades, considerable attention has been paid to the results of developments in the states of the former Soviet Union, particularly Russia. The traditional Russian approach has been to design wingships as ships that fly and not as aircraft that land on the water. This approach avoids the complexities of design and safety requirements associated with aircraft certification. With this philosophy, a 270 knot wingship can indeed be considered the fastest type of marine craft afloat.

2.2 Wingship Definition

A wingship is a water-based flying craft designed to exploit drag-reducing ground effect by flying the majority of its design mission very close to the surface of the water. This definition excludes amphibious craft which can also take off and land on land or can taxi from land to water and from water to land under their own power. Wingships are a subclass of wing-in-ground effect (WIG) vehicles. This larger class includes all craft intended to exploit ground effect—independent of surface being flown over (water, land, ice) and the basing.

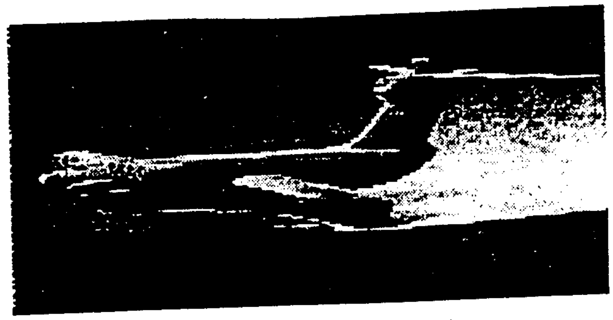
To solidify definitions, Figure 2.2-1 depicts a large Russian WIG, two Russian wingships, and a contemporary large wingship concept. Traditional names associated with this general technology area are: ram wing; wing-in-ground effect (WIG); and ekranoplan (Russian). The specific technique of aiding takeoff and, perhaps, landing by directing the efflux of forward mounted propulsion units under the wing is called air injection in Russia and power augmentation or power augmented ram (PAR) in the U.S. In the remainder of this report, we will use the term WIG to refer to any vehicle designed specifically to take advantage of surface effect and the term wingship to refer to water-based WIGs. We will use PAR and air injection interchangeably.

2.3 Overview Of Transportation Systems

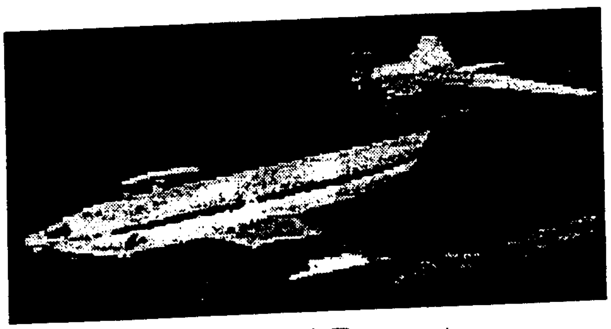
To properly compare widely diverse types of transportation vehicles, one needs several fairly general quantitative measures and ways of representing many of these measures together.

The productivity of a transport vehicle is roughly proportional to the product of the efficiency and speed. The Karman-Gabrielli (K-G) plot is a convenient way to represent the efficiency (which is proportional to range for fixed weight fractions), speed (which has value of its own), and productivity (which is the product of the other two). Figure 2.4-1 is an example of the K-G plot. This figure indicates the relative performances of aircraft, ships, and wingships. Figure 4.1.2-1 combines information from the Wingship Compendium (Section 5, Ref. 5.1-2) with 5,000 ton wingship design goals. The figure includes demonstrated performance, estimated performance, and performance goals. Wingships are potentially slightly more efficient than transport aircraft and are much faster than ships.

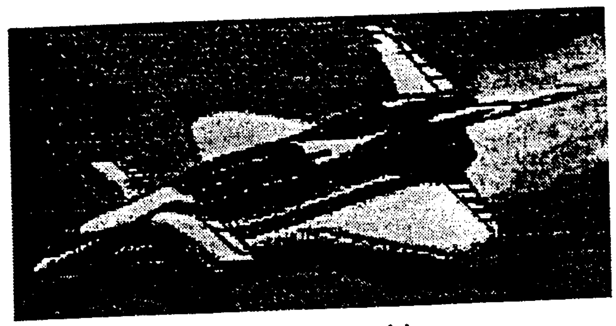
540 Ton Wingship Test Craft
(Caspian Sea Monster)



400 Ton Wingship
(Lun)



140 Ton WIG Transport
(Orlyonok)



5000 Ton Wingship
(Concept)

Figure 2.2-1 Two Wingships, One WIG, and a Wingship Concept

Another key parameter is the useful load (defined as the sum of fuel and payload). The useful load as a fraction of gross weight is primarily a function of: (1) materials and structures technology and structure shape; and (2) the maximum power or thrust available and propulsion technology. Figure 2.4-2 from a paper by Cleveland shows that useful load fraction of aircraft is a function of the gross weight and that it has generally improved over time up to weights of about one million pounds. Another interpretation is that improvement in structural and propulsion technologies have enabled the construction of increasingly large, practical aircraft. Any craft can achieve various combinations of range and payload depending on how the useful load is divided between fuel and payload.

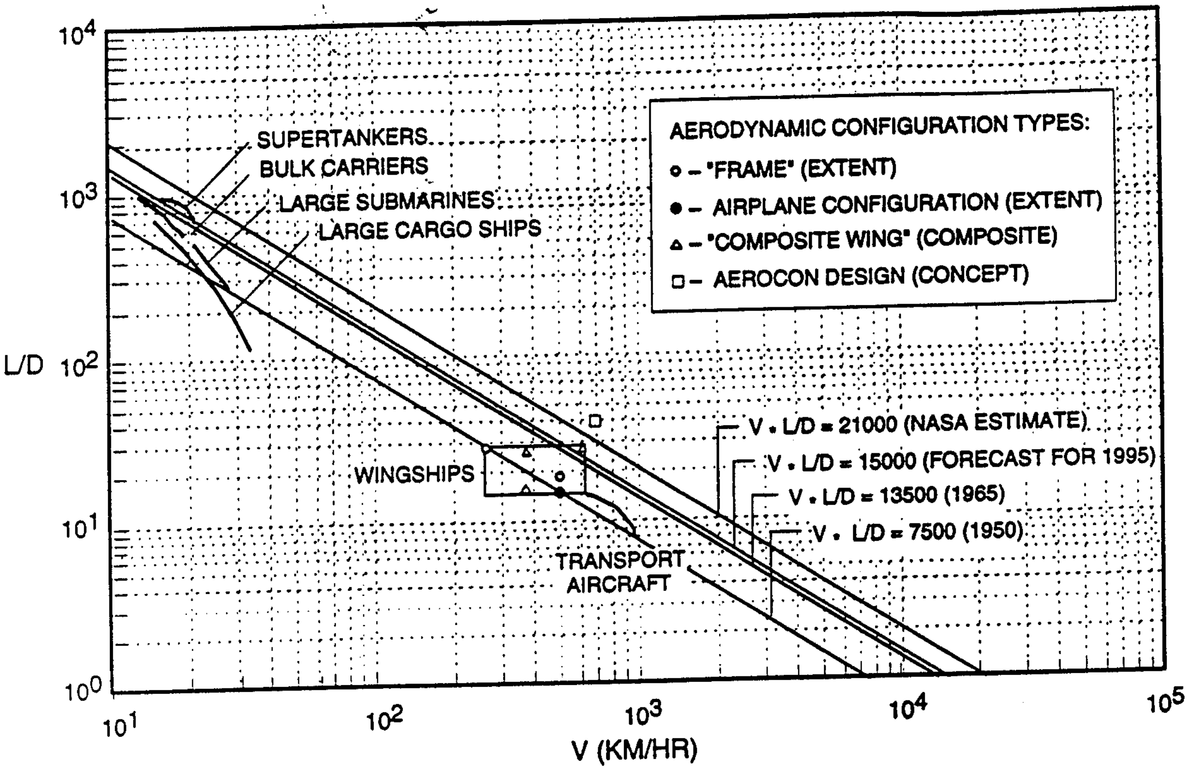


Figure 2.4-1
Karman-Gabrielli Plot Showing Transport Efficiency of Diverse Vehicle Types

2.4 Wingship Promise

The central attractiveness of wingships has been the perceived improvements in aerodynamic efficiency compared to aircraft. During the 1960's, numerous WIG vehicle technologists focused on the apparent "hole" in the K-G plot as an opportunity for new types of craft. If vehicles could be designed to fill this hole, they would have better range and payload performance than aircraft, and speeds much faster than ships. WIG craft can arguably fill this void by flying very close to the surface (less than one-tenth of the span). Cruising at this altitude reduces drag by about 25% and

reduces speed by about 20%. Therefore, for the open ocean application with given wave heights, bigger is better.

Another key argument for the viability of wingships is the avoidance of the requirement for airports and runways. Since over two-thirds of the planet is covered by water (much of it in large contiguous bodies), this fact also is a compelling argument to consider these types of flying craft.

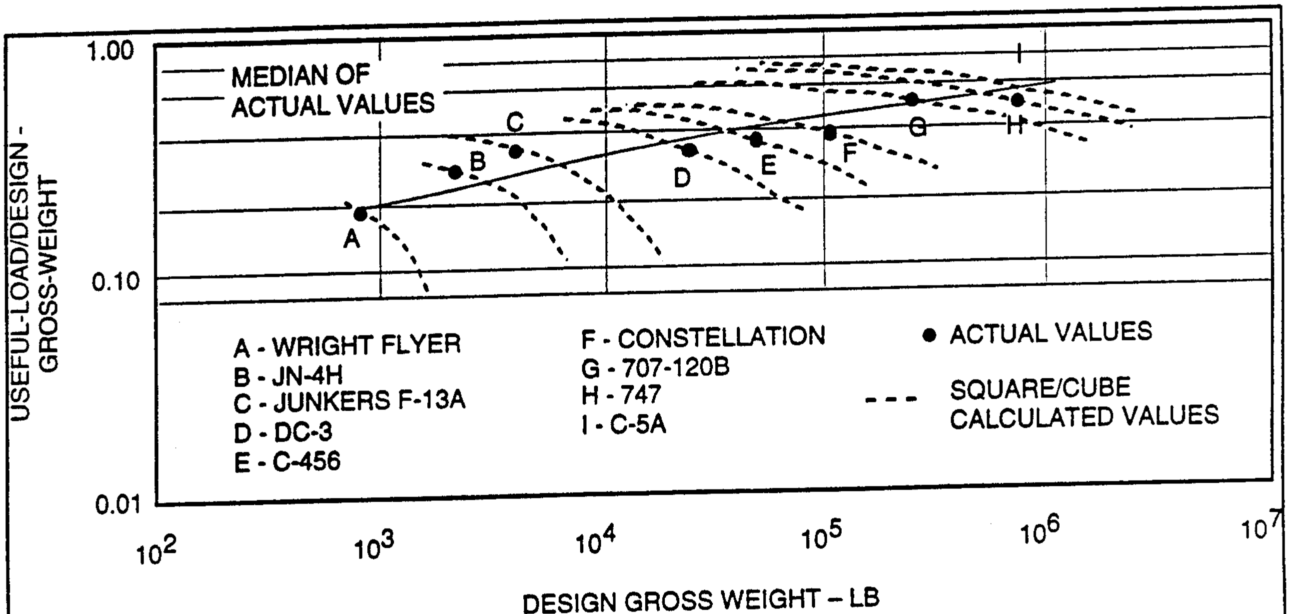


Figure 2.4-2. Useful Load Fraction of Aircraft

Wingships and seaplanes are waterborne platforms that take advantage of the broad water surface for takeoff and landing. This gives the platform the advantage over landbased aircraft of not being limited by landing field location and dimensions for operation. Militarily, they can operate in areas with non-prepared landing surfaces as long as the payload can be unloaded. They may be commercially viable since many of the commercially important cities worldwide are located at a shoreline. The expanse of the water also lets the wing span of the platform be larger than limits placed by standard runway widths, allowing spans of greater than 200 feet. It also allows longer takeoff distances if needed. The largest wingship built to date uses captured air pressure under the wings provided by a separate power system to augment the dynamic lift provided by the fuselage in contact with the water and aerodynamic lift on the wings to achieve lift-off. The seaplane gets its takeoff lift from water dynamic lift on the fuselage and aerodynamics. The choice between which platform is selected for the mission is based on aerodynamic performance, power required for takeoff and cruise, fuel usage rate, and payload fraction.

2.5 Wingship Limitations And Risks

Since the wingship depends on surface effect to increase its lift and obtain relatively long range, it is useful only on routes that have a long run of naturally and reliably smooth surface, such as water. This study has concentrated on over water applications. Special care has been taken to assure practical cruising heights with respect to the natural state of the ocean.

In Russia, as in the US, there are differences of opinion on the performance and technical requirements of wingships. These differences are made apparent in the trip reports (Appendix G). However, description of the performance actually achieved so far and descriptions of how the craft operate were remarkably uniform.

Practical considerations, such as reduced cruise speeds (compared to landplanes) and oversized engines (relative to cruise power requirements) tend to detract from the promise. Therefore, any serious comparison of vehicle types must include these negative aspects as well as the positive increase to aerodynamic efficiency.

Among the remaining technical risks or uncertainties are the design of structure to tolerate water impact pressures and overall craft accelerations associated with clipping the tops of waves at cruise speeds. Also, there is some remaining uncertainty as to how to design for the rogue wave phenomena.

The Russians currently use aviation engines adapted for the sea environment. Future engines must be fully marinized and designed for the large difference in power requirements between takeoff and cruise and for engine shutdown, if required. Designs must achieve adequate reliability, maintainability, and availability.

2.6 Purpose

This ARPA report will strive to:

1. Provide an objective assessment of the feasibility, performance potential and limitations of wingship-type, surface effect vehicles, incorporating considerations of both available and projected (emerging) technologies.
2. Provide a preliminary assessment of the mission utility of these vehicle types in satisfying defense, heavy lift needs, and other potential missions, considering both available and other projected defense assets; and
3. Provide a preliminary recommendation for future development activities (roadmap) based on performance, mission utility and development risk reduction.

2.7 What The Report Contains

At the top level, this evaluation addresses two primary questions. First, with some technology stretch, what kind of performance can we expect to achieve with wingships? Second, does that level of performance produce a significant improvement in capability when compared to other

methods of accomplishing the same transport job (Appendix B). Preliminary issues and questions are addressed in this context.

In this report, Section 3 describes the methodologies and procedures used to arrive at our conclusions. Section 4 is a discussion of certain ground rules and assumptions used to define and limit the scope of this study so quantitative, confident, and valuable results are produced. Section 5 describes the state-of-the-art of the most important technologies influencing the performance and utility of this type of craft. Section 6 synthesizes the technical results into an overall evaluation of technologies and concepts. Section 7 encompasses a preliminary evaluation of mission utility, including a comparison of the wingship to other ways of meeting the requirements of the long range supply missions. Sections 8, 9, and 11 are the results of our study. They are, respectively, Significant Technical Findings, Conclusions, and Recommendations. Section 10, Taxonomy of Demonstrators, is between Conclusions and Recommendations to provide context for the recommendations and clearly explain the Russian programs in language familiar to our research and development community.

Thirteen appendices support the conclusions and assertions in the body of the report.

3. Methodology and Procedures

To conduct this initial investigation, a panel of experts convened to examine concepts and technologies. An initial technical group, known as the Wingship Technical Evaluation Team (WTET) was formed on March 1, 1993. (See Figure 3-1a) A second panel known as the Wingship Missions Analysis Team (WMAT) was formed in August 1993 to investigate this area. Figure 3-1b shows the institutions and WMAT with their general areas of expertise and responsibility. As of this report date, the efforts of the latter group are ongoing. These include definition of potential missions and comparisons with competing approaches. A variety of disparate missions including heavy lift, missile carrier and launcher, delivery of special operations forces equipment, and delivery of deep submergence rescue vehicle are considered. Due to late Congressional approval, this report contains only a preliminary evaluation of wingship applications.

The study team included nationally recognized specialists and generalists representing many different organizations. Various government defense organizations as well as shipbuilding and aircraft industries, and academia were represented. The team included expertise on all critical vehicle technologies. The investigation included extensive interaction with the Russians [see Figure 3-2] since they have invested great time and effort in recent development of these vehicles. Numerous Trip Reports are in Appendix G.

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Navy Liaison / Russian POC	CAPT Ed Pope, USN, OCNR
Navy Liaison	John Fraas, USN, ONR-SOP

Technical Evaluation Team

WIG Expert	Bob Wilson, DTRC
Flight Controls	Joe Gera, NASA - Dryden
Structures / Aircraft Design	Burt Rutan, Scaled Composites
WIG Designer	Len Malthan, Northrop
WIG Expert	John Reeves, NAWC - AD (Warminster)
Aerodynamicist / Designer	Stephan Hooker, Aerocon Inc.
Aeronautics Expert / Aerodynamicist	Dr. Eugene Covert, MIT
Infrastructure / Support	Hal Fluk, NAWC-AD (Lakehurst)
Propulsion Experts	Eric Lister, SRS Technologies
WIG Specialist	Jim Camp, DTRC
Ship Structures	Dieter Czimmek, Newport News Shipbuilding
Hydrodynamicist / Seaplane Expert	Dr. Dan Savitsky, Stevens Institute of Technology
Mission Analyst (Sealift)	C.F. Snyder, DTRC

Figure 3-1a. Wingship Technical Evaluation Team (WTET)

Aeronautical Systems Center, Wright-Patterson AFB	Strategic Lift Analysis, Cost and Effectiveness
BDM Federal, Inc.	Strategic Lift Analysis, Impact on Warfighting Capability, WIG Combat Applications, Assist with Final Report
DSA, Inc.	Strategic Lift Analysis, Contingency Response
Lockheed, Aeronautical Systems Company	Strategic Lift Analysis, Loadability, Warfighting Impact, Force Closure, Lift Cycle Costs, Commercial Operations
Military Traffic Management Command, Transportation Engineering Agency	Strategic Lift Analysis, Loadability, Deployability
Naval Air Warfare Center, Warminster	WIG Military Mission Applications
Naval Surface Warfare Center, Carderock	MAR Team Leadership, Life Cycle Cost Estimates, Final Report
Naval Surface Warfare Center, White Oak	WIG Military Mission Applications
Northrop Corporation	Wig Concept Design, Technical Assessment, Military Missions
Stanley Associates	Review of Strategic Lift Analyses, Assist with Final Report

Figure 3-1b. Mission Analysis Team Task Assignments

Russian Participants

Government

VAdm Venomin Poliansky	Director, Naval Shipbuilding
MGen Viktor Miranov	Vice Chmn. Comm on Military-Technical Policy, MoD
Capt (Col) Andrei Logvinenko	Ministry of Defense
	Research Shipbuilding Inst. MoD
Capt (Col) Mikhail Malyshev	Navy Wingship Office
Capt (Col) Nikolai Baranov	

Industry

Central Hydrofoil (Alexeev) Design Bureau
Volga Plant (Fabrication)
Beriev Design Bureau
Kazan Engine Design Bureau
Elektro - Pribor (Autopilots) of St. Petersburg

Institutions

St. Petersburg Marine Technical University
Central Aero Hydrodynamic Institute (TsAGI)
Krylov Shipbuilding Research Institute
Irkutsk State University
The Engineering Academy of Russia

Figure 3-2 Russian Participants

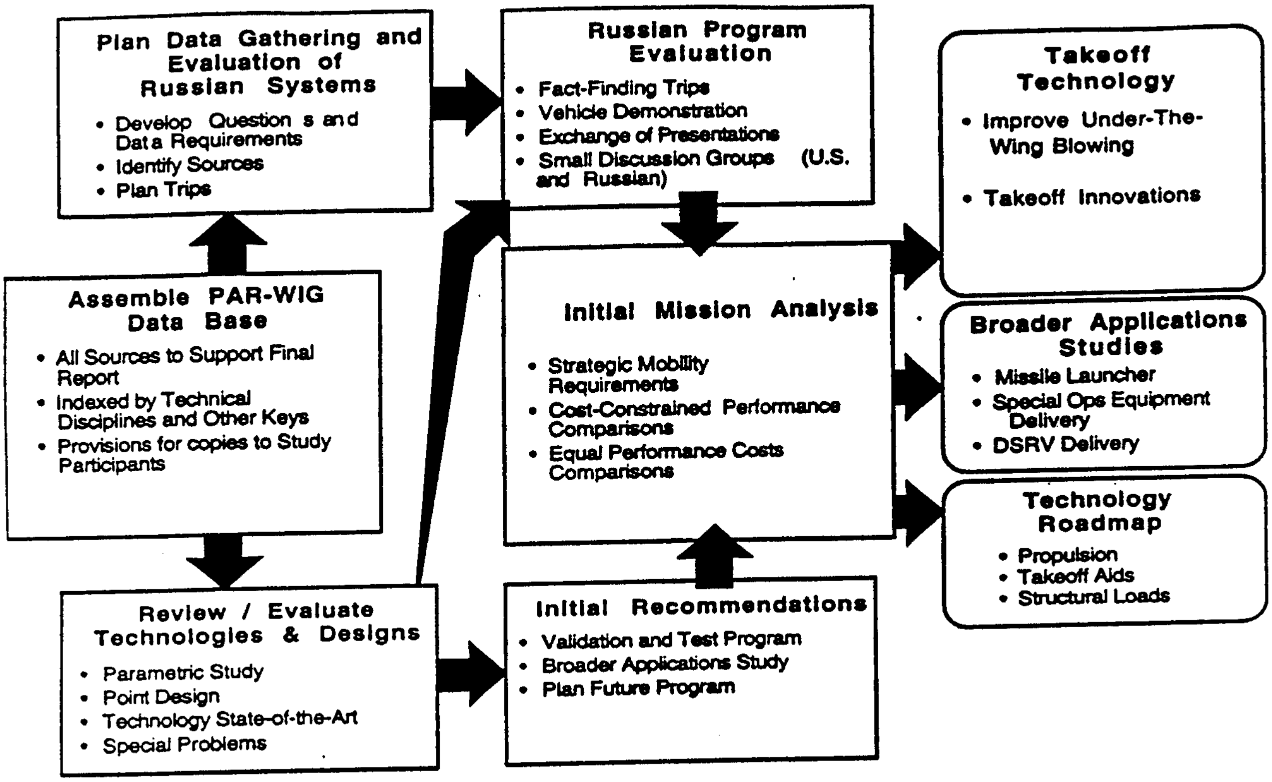

Figure 3-3. Wingship Study Work Breakdown

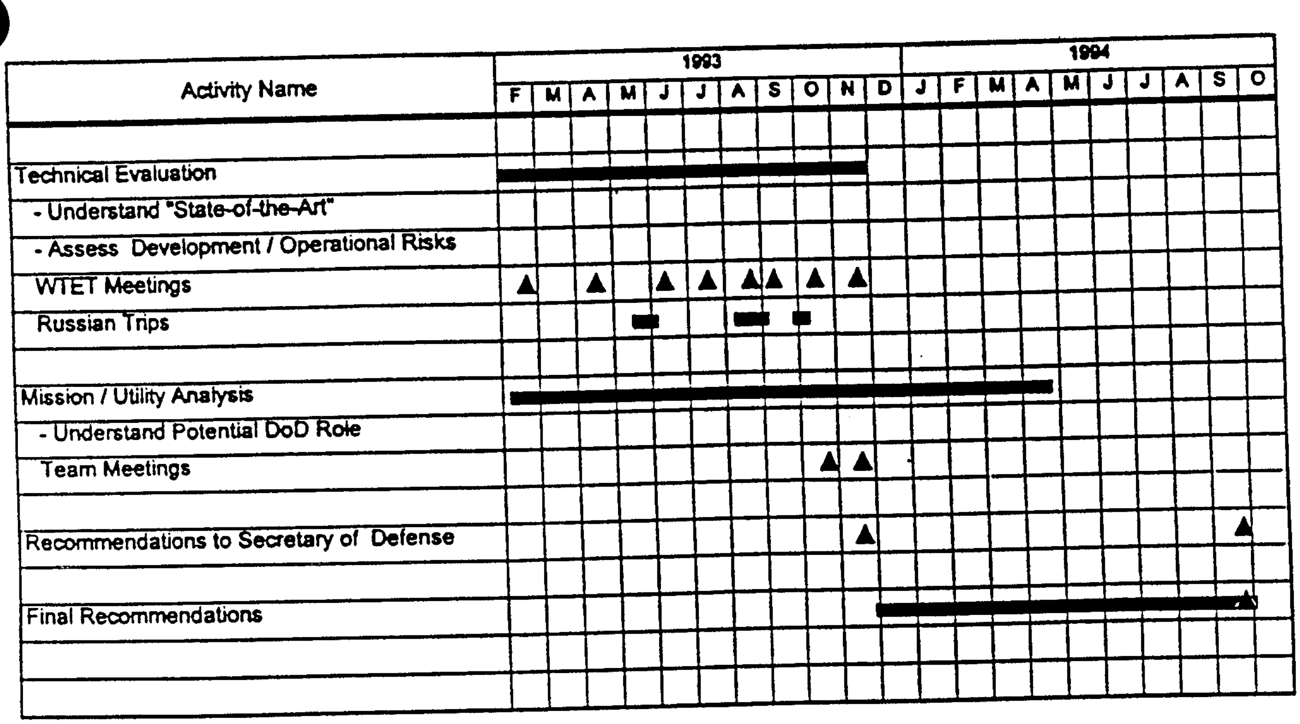

Figure 3-4. Schedule

Figure 3-3 depicts the top level task flow of the study. Figure 3-4 depicts these activities in a schedule format.

Among the first activities was the development of an extensive bibliographical database. This database provided the WTET with all references relevant to the evaluation and with reliable data and analysis to support all technical assertions and projections in this report.

The specific tasks for the Technology/Design Assessment Team were:

1. Conduct literature review of all pertinent literature related to/oriented toward wingship concepts.

2. Synthesize results to surface strengths and limitations.

3. Prepare plan for assessment of Russian activities/progress in wingship development.
   - Lay groundwork for initial visit including coordination with key Russian industry/government players.
4. Visit Russian facilities and personnel - provide preliminary assessment of capabilities and Russian 'state-of-the-art.'
   - Conduct interviews with Russian designers and technologists
   - Review available documentation.
   - Review Requirement for additional visits including nature and scope of follow on activities.
5. Synthesize initial results of wingship technology assessment with other recent technological developments/trends which may enhance wingship performance and/or operability or which reduce development or operational risks.

6. Provide continuing coordination and interface with the mission analysis team.

7. Support integration of results with mission analysis to generate recommendations.

The specific tasks for the Mission Analysis Team were:

1. Provide initial operational analyses of several viable candidate wingship concepts to assess mission effectiveness and utility in candidate mission scenarios. Mission areas to be considered include:
   - Heavy lift applications
   - Missile carrier and launcher
   - Delivery of special operation forces equipment
   - Delivery of deep submergence rescue vehicle

2. Identify system requirements necessary to assure wingship concepts are competitive with other related systems, incorporate full range of mission parameters including: ingress, egress, loading, unloading and infrastructure considerations. Also incorporate survivability/vulnerability considerations in the analysis.

3. Identify limitations/shortcomings arising from these analyses.

4. Provide continuing coordination and interface with the technology analysis team.

5. Support integration of results with the technology assessment leading to recommendations on further activities.

4. Ground Rules And Assumptions

To provide a competent and credible evaluation in the available time, it was necessary to limit the scope with a rational set of ground rules and assumptions. A different set of ground rules and assumptions could lead to other conclusions. Therefore, the reader should attempt to understand the implications of these ground rules and assumptions.

4.1 General Classification

This study considered only craft whose design was greatly influenced by aerodynamic ground effect. Our parametric study considered only craft that were intended to operate in strong ground effect over the open ocean for a large fraction of their missions. Water basing alone has potential military utility, whether or not the vehicle concept uses ground effect. This study did not consider these more general types parametrically. In any design driven by a set of mission requirements, designers should certainly consider various arrangements of hydrodynamic features, under the wing blowing, and conventional ground effect to design the least expensive craft that meets their mission requirements.

The parametric study generates a family of craft geometries of various sizes and performances from which the utility and mission analysts can choose to do their analysis. Depending on the mission scenario, smaller or larger craft may be desirable. Each design in a parametric base is optimum by some measure. We chose to optimize the performance parameter range because our initial focus was on strategic supply missions.

4.1.1 Focus On Non-Amphibious

The study focused primarily on non-amphibious WIGs. By non-amphibious we mean that the craft (1) cannot take off or land on land; (2) cannot taxi from the water to the land or from the land to the water on self contained beaching gear. The reason for this limit is that providing amphibious capability increases empty weight fraction and detracts from performance. There were some exceptions. For example, the Orlyonok vehicle which was demonstrated and is discussed in this report is an amphibious vehicle.

4.1.2 Consider Only Aircraft-Configured Craft With A Takeoff And Landing Aid

Figure 4.1.2-1 compares the required thrust-to-weight ratio and the design aspect ratio of a number of water-based craft. Lower aspect ratio is desirable to reduce wing structural weight. Inclusion of a takeoff aid such as PAR reduces the thrust required for takeoff by about 15%. Craft designed for altitude flight have significantly higher aspect ratios.

High craft density and high weight-to-thrust ratio are especially important for wingships (as compared to aircraft) in order to achieve the speed required for productivity, the engine efficiency required for range while operating at sea level, and the structural integrity required for takeoff and landing.

Even limiting our attention to wingships with takeoff and landing aids does not define a narrow enough class to permit good estimates of achievable performance over a wide range of sizes and proportions. Consequently, we chose to further limit the parametric part of the evaluation to the airplane-type configurations (i.e., wing, body, and tail) with air injection.

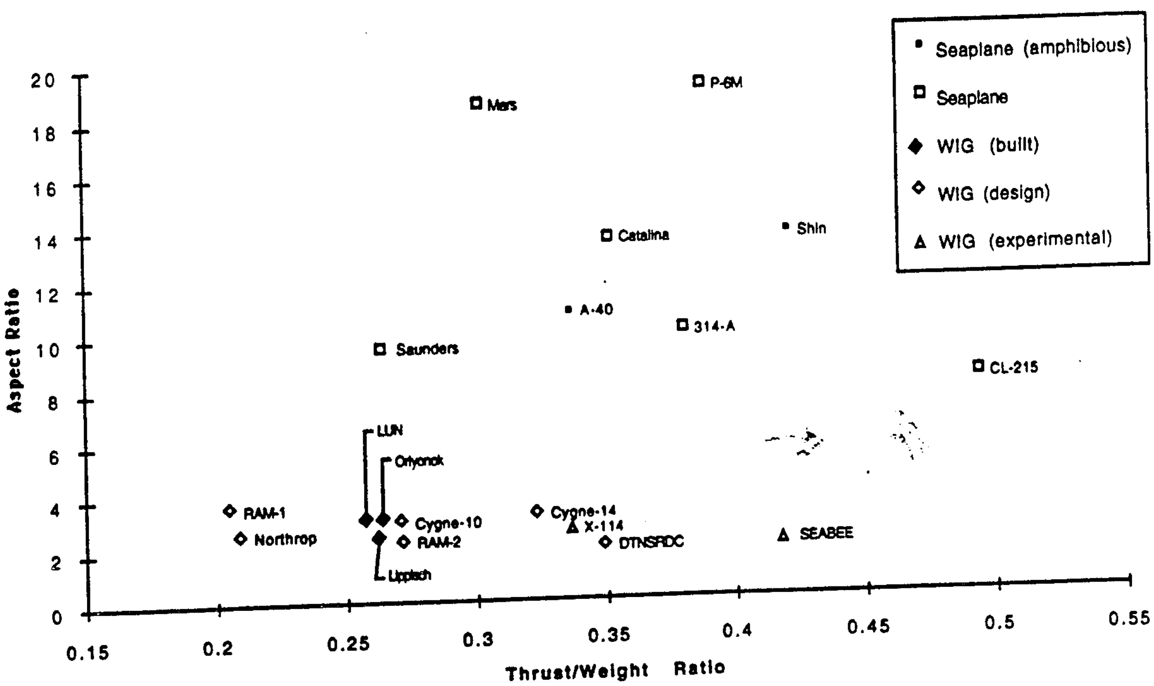

Figure 4.1.2-1. Comparison of WIG and Seaplane Characteristics

A limitation resulting from this ground rule is the parametrics do not accurately represent other configuration types, such as flying wings. Since the optimum very large wingships might have a significantly different type of planform, our parametric results are not totally comprehensive.

4.2 Technology Limitations

We have limited our attention to foreseeable technology available dates, to low technical risk, and to a scale range bounded on the lower end by the largest modern wingship and at the upper end by a 5000-ton concept.

4.2.1 Development Time Frame

We limited technology stretch to about 10 years. The following section on wingship development history indicates that vehicles developed to date are not nearly big enough and do not have enough range and payload performance to be of much interest for strategic mobility. Further, it is apparent that simple scale-up of existing designs does not result in adequate performance. Part of the reason for this inadequacy is that the existing large designs do not use modern high performance engines and the materials and structures are not as light as they could be. Therefore, for the purposes of this evaluation, we had to select a reasonable level of technology stretch. We based out parametrics on technology we expect to be available to support a design in about five years. Assuming that it would take at least another five years to design and build the first example, we are considering craft that could be in service about 2005.

4.2.2 Low Risk Technology Application

We generally took a low technical risk approach because the smallest craft that could be attractive on the long range missions are large enough to require major capital investment and would have to be "right" the first time. So that our evaluation is even-handed, we assumed the same level of technology (structures, propulsion, etc.) for other vehicle (e.g. seaplanes) approaches to the same problem.

4.2.3 Risks Associated With Large Designs

Knowledgeable Russian designers estimate the maximum increase they would be comfortable with is from the present 400 metric tons to a range of 800 to 2000 metric tons, depending on the individual. Significantly, Dr. Sokolov, a man with extensive hands-on experience (he survived the recent crash) suggested 800 tons. He said that the 800 ton machine would be a flying wing if it was to carry passengers. (Ref. Appendix G) A flying wing of this size would not have large enough internal dimensions for military vehicles. A 1200 ton estimate, again a flying wing, came from an academician, Logvinovich, who generated scientific data for wingship design. (Ref. Appendix G) The 2000 ton estimate came from Dr. Chubikov, the director of The Central Hydrofoil Design Bureau. (Ref. Appendix G) The sense of our committee is that an increase of a factor of two in gross weight is risky. That is not to say that some level of research and design study should continue on the very large craft. It does say that the technology does not support a very large design that could be built before 2005.

5. Definition of The State-of-the-Art

Three important elements must be reviewed when describing what defines the state-of-the-art for wingship science and technology: the history of wingship development which resulted in significant test or demonstration craft; previous technology and applications studies; and the various technologies supporting wingship design.

5.1 Short History Of Worldwide Wingship Developments

In 1929, the Dornier DO-X seaplane was constructed. In 1930-31, this 56-ton seaplane used the ground effect to increase its range and payload during transatlantic flights (Ref. 5.1-1).

In 1935, Toivo Kaario of Finland built an experimental wing-in-ground effect vehicle. It was powered by a 16 hp engine and carried a man over the snow at speeds up to 12 knots (Ref. 5.1-1). He obtained the first patent for a surface effect craft (Ref. 5.1-2 pg 6).

In 1958, R. Ye. Alexeyev began a project to create his first wingship model for the Russian Navy (Ref. 5.1-2 pg 12). This work led to the construction of the SM-series ekranoplan test vehicles, most of which were built/tested in the early- to mid-1960's (Ref. 5.1-2 pg 15).

In 1961, the SM-1 achieved a speed of 200 km/hr and demonstrated wingship stability and dynamic parameters near the surface. Major disadvantages proved to be high takeoff and landing speeds, and over-sensitivity to surface roughness (Ref. 5.1-2 pg 16).

In 1962, Alexeyev was the first to incorporate under-wing blowing to improve the takeoff and landing aerodynamics of the SM-2 model. The blowing system, however, aggravated the pitch stability problem in a tandem wing configuration (Ref. 5.1-2 pgs 16, 20).

In 1962, Kaario developed the Aerosani No.8, a two-man sled capable of speeds up to 43 knots (Ref. 5.1-1).

In 1963, Dr. W.R. Bertelson of Illinois, designed the GEM-3, a four-seat ram-wing vehicle capable of speeds up to 95 knots over snow or water (Ref. 5.1-1).

In 1963, Alexander Lippisch of West Germany, developed an experimental WIG vehicle, the X-112, at the Collins Radio Company in Iowa. Initial testing demonstrated the vehicle to be stable in both free flight and ground effect (Ref. 5.1-1).

In 1963, Alexeyev devised a pitch stability solution by taking the aft wing away from the influence zone of the forward wing, and out of the blowing zone. This led to the airplane-type configuration used in most of the subsequent Russian designs, characterized by forward wing-in-ground-effect employing underwing blowing and an aft wing out of ground effect. During this same year, the SM-2P, which used this configuration, was built and tested (Ref. 5.1-2 pg 20).

In 1963-65, additional self propelled models, the SM-3, -4, -5, and -8, were constructed and tested. These prototypes represented important developmental steps in the ekranoplan design process and provided the data necessary for the construction of a much larger ekranoplan (Ref. 5.1-2 pg 20).

In 1966, Project KM (known in the U.S. as the Caspian Sea Monster) was constructed and launched. Extensive testing between 1966-69 confirmed design data for large ekranoplans, thus, KM became the model for future Russian ekranoplan development. In particular, the tests confirmed flight in ground effect at speeds over 500 km/hr (Ref. 5.1-2 pg 26). See Figure 5.1-1.

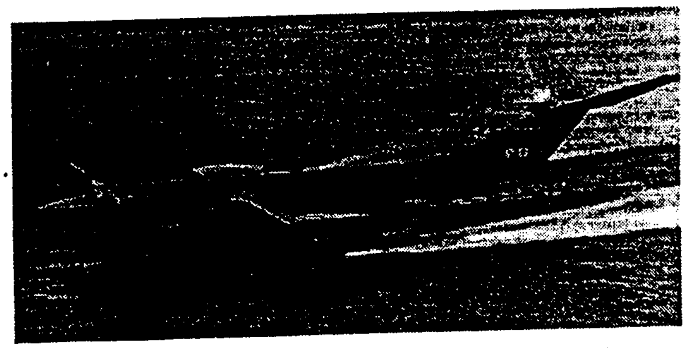

Figure 5.1-1
Project KM (Caspian Sea Monster) first flown in 1966.

In 1967, a crew training ekranoplan, named the UT-1, was designed and constructed under Alexeyev's supervision (Ref. 5.1-2 pg 20).

In 1970, Lippisch developed the X-113 under a joint program with the West German government and Rhein-Fleuzeugbau. In 1971-72 the vehicle was extensively tested to collect data on sea states with waves approaching 1 m and winds up to 25 knots (Ref. 5.1-1).

In 1972, the SM-6 was designed as a prototype for the ORLYONOK ekranoplan. This vehicle was approximately one-half scale (Ref. 5.1-2 pg 26).

In 1972, HFL-Seaglide Ltd. of England, under the direction of Ronald Bourn, developed a three-seat aerodynamic ram-wing vehicle called SEABEE. The vehicle was controlled by an aircraft-type elevon on the horizontal stabilizer and twin aerodynamic rudders. It was tested in the ground effect mode only (Ref. 5.1-1).

In 1978, NSRDC tested a PAR-WIG radio controlled model which was powered by two 1 hp model aircraft engines. It cruised at an altitude of 3 inches and a velocity of 20 knots (Ref. 5.1-1).

5.2 General Discussion Of Large Russian Configurations

Project KM (known in the U. S. as the Caspian Sea Monster)

This was a one-of-a-kind test vehicle with the purpose of demonstrating that ekranoplans of large size could be designed, constructed, and flown to theoretical performance levels. It was built in the early- to mid-1960s and flew until its crash and destruction in the early 1980s.

ORLYONOK (known in the U.S. by its NATO designator ORLAN)

Several of these vehicles were constructed from the mid-1970s to the early 1980s to demonstrate an amphibious ekranoplan capability. Flight tests for these vehicles may have been conducted from the late 1970s until the present. One of the vehicles was reported to have crashed in the summer of 1992.

LUN (known in the U. S. by its NATO designator UTKA)

This one-of-a-kind vehicle, which was designed to demonstrate the concept of launching surface-to-surface cruise missiles from an ekranoplan, was constructed in the mid-1980s, and may have been flight tested from the late 1980s until the present. Presently under construction is a second version of this configuration, the SPASATEL, which is intended for rescue work.

	Year	Length(m)	Span(m)	Speed(km/hr)	Total Thrust(MT)	Displacement (MT)
Project KM	1966	92	36.4	400-450	110	540
ORLYONOK	1972	58	32	350	37	120
LUN	1980's	73.8	44	450-550	104	400
SPASATEL	1990's	73.8	44	450-550	104	400

Figure 5.2-1
General Characteristics of Russian Configurations

5.3 Principal Results Of Earlier Studies

Due to the sensitive nature of the material involved, certain portions of the Principal Results of Earlier U.S. Studies will be disclosed only in Appendix H.

October 1956: Douglas analysis demonstrates that when operated in ground effect, a low aspect ratio wing develops a greater percentage improvement in lift than a higher aspect ratio wing of the same area.(Ref. 5.3-1)

1963: Alexeyev develops underwing blowing, later called power augmented ram (PAR) in the U.S.

Winter 1963: Lockheed conducts wind tunnel tests of low aspect ratio wings to support Lockheed Marine Vehicles Division (ASW and Ocean Systems Organization) under contract to DoD.

Spring 1964: Lockheed publishes results of tests (Ref. 5.3-2). Report demonstrates significant aerodynamic efficiency to be gained from ground effect flight.

1966-69: Central Hydrofoil Design Bureau (CHDB)/Soviet Navy confirms that ground effect flight with a large-scale ekranoplan (Project KM) is possible at speeds over 500 km/hr.

1970s: No significant U.S. interest with the exception of Lockheed and Douglas Aircraft Companies' studies of ANVCE PAR WIG designs. These designs demonstrate that favorable empty weight fractions are possible and small sizes chosen are unable to improve performance significantly by using ground effect over the open ocean.

1980's NSRDC conducts design studies to examine 2,000 ton PARWIGs for payload rapid delivery. The studies were conducted for the Marine Corps and NAVSEA under the CONFORM program.

5.4 Technology Levels And Uncertainties

The current level of technology, including uncertainties in aerodynamics, stability and control, propulsion, structures, and hydrodynamics, greatly affect the ability to design capable vehicles. For this application, hydrodynamic technologies include takeoff and landing aides such as under-the-wing blowing and hydroskis.

5.4.1 Aerodynamics

The existence of a ground effect has been recognized since the earliest days of flight. Attempts to quantify its impact on lift and drag were first published by NACA in 1922 (Ref. 5.4-1). For commercial and military aircraft, ground effect is a phenomenon which is encountered only briefly during takeoff and landing, lasting 20 to 65 seconds during takeoff and less during landing. While in ground effect, aircraft are usually at moderate to high angles of attack with landing gear and lift augmentation devices deployed, all of which contribute significantly to high profile drag. For an aircraft designer, ground effect is considered to ensure that sufficient elevator effectiveness, aircraft rotation, and climb attitude control are provided during takeoff for all anticipated c.g. positions. During landing, the influence of ground effect on elevator control is considered, as well as its influence on the nose-down pitching moment due to flap deflections.

When a wing nears a surface, a change occurs in the three dimensional flow pattern because the local airflow has no vertical component at the surface. As the vertical or downwash velocity is reduced, the so called "induced angle of attack" is reduced. As the induced angle of attack is reduced, the slope of the lift curve increases, so that for a fixed angle of attack the lift is increased. Further, the reduced value of induced angle of attack also results in a reduced value of the induced drag. A smaller angle of attack is required near the surface to produce a given amount of lift versus that required in freestream conditions at altitude or roughly one span height or more (depending on the planform) above the surface. For the same lift the induced drag is reduced, reducing the thrust required for a given lift. When an aircraft is sufficiently near a surface, the flow in the confined region beneath the wing and wake approach a two-dimensional channel flow with known boundaries and known mass addition, coming from the flow tangency boundary condition on the lower surface. (The lift coefficient of the wing, with the upper surface neglected, is only a function

of the planform and shape of the wing's lower surface [Ref. 5.4-2]). The reduction in induced drag has prompted engineers to conceive platforms usually referred to as WIGs that would fly in ground effect.

This section of the report briefly discusses: aerodynamic efficiency; the basis for ground effect theory; experimental technique; lift; drag; and moment and trim of WIGs. Section 5.4.6 discusses the air injection feature that is applied to Russian WIGs.

5.4.1.1 Aerodynamic Efficiency

The aerodynamic efficiency of landplanes at cruise altitudes generally ranges between 9 - 21 for military aircraft and between 13 and 20 for commercial aircraft (Ref. 5.4-3). The Russian aerodynamic efficiency data at cruise ranged between 15-18 for existing WIGs for relatively low cruise heights of three to five feet above the water surface. Reference 5.4-4 claims an L/D of 20 - 25 for cruise between 1.5 and 3.0 feet above the sea for a proposed 10 metric ton WIG (with a wing span of 41 feet and wing aspect ratio of 1.71). These claims were based on the demonstrated L/D of the X-113. Out of ground effect L/D is estimated as 9.9.

h/b = Trailing Edge Height to Span Ratio

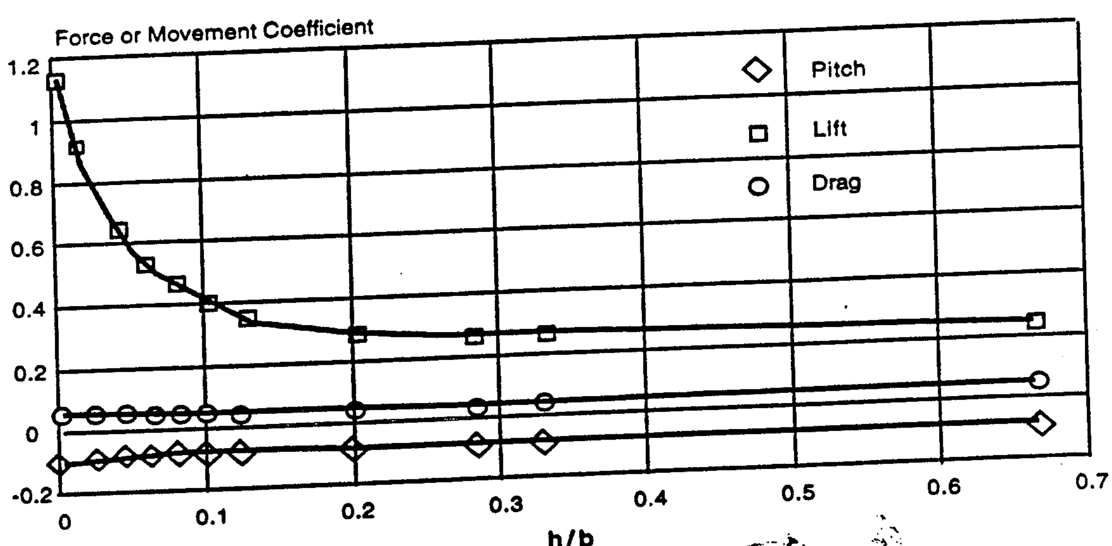

Figure 5.4.1-1
Force and Moment Coefficient Variation

Figure 5.4.1-1 shows the variation of force and moment coefficients for a WIG configuration wind tunnel tested in 1965 (Ref. 5.4-5). As can be seen, the most predominant improvement in C_L, and therefore L/D, occurs at trailing edge height/wing span (h/b's) between 0.0 and 0.2. The improvement increases more rapidly as the lift coefficient increases and as the surface clearance decreases. The high lift coefficients imply that for WIGs to be efficient, they must be slow speed platforms, (slower than airplanes) unless high wing loadings can be used.

Reference 5.4-6 showed that there was a significant correlation between heave accelerations and the significant wave height for Hovercraft. When the waves encountered the hard structure, heave accelerations increased dramatically. Thus, for the WIG, an appropriate ground rule is that the height of the wing bottom surface above the bottom of the endplate, pontoon or hull (whichever is lowest) should be equal to the significant wave height for takeoff and landing.

Figure 5.4.4.1-1 shows wave heights corresponding to various wind speeds. As the sea becomes rougher, greater wing clearance heights are required. Greater wing clearance heights (which in cruise is roughly the median height between the wave trough and crest + the normal cruise height) reduce aerodynamic efficiency. Thus, for a WIG to have significant rough weather capability, it must be large.

Wind tunnel tests of isolated wings such as those in Reference 5.4-7 usually show extremely high L/Ds, especially when close to the ground board. When a complete conventional aircraft configuration is tested, however, L/D is substantially reduced and may be one-half to one-quarter of the isolated wing. The primary reasons for this are the additional drag of the hull or fuselage, the addition of endplates, and finally, a large stabilizer to trim out the pitching moments experienced in ground effect. In addition, the flow field over the fuselage modifies the spanwise load distribution over the wing, possibly increasing drag. When the fuselage or hull is designed similar to a seaplane hull, an increase in drag results. This increases the drag relative to an isolated streamlined fuselage used on modern airliners. The result is a loss of L/D between 7 to 15% (Ref. 5.4-8) relative to a well designed commercial aircraft.

As previously stated, ground effect has been considered as a low speed phenomena in the West, therefore, very little is known with regard to ground effect at high subsonic Mach numbers. Reference 5.4-9 suggests that improvements in L/D at high subsonic Mach numbers may be obtainable. References 5.4.10 and 5.4.11 contain some evidence supporting this possibility. High subsonic cruise, however, would require even greater wing loading thus making the takeoff problem more difficult.

5.4.1.2 Basis Of Ground Effect Theory

As a first approximation, a high aspect ratio wing is modeled by a bound vortex and two trailing vortices. The effect of a ground plane on this "horseshoe" vortex system is represented by placing a mirror image of the vortex system two ground plane heights below the vortex system representing the wing. The resulting plane of symmetry satisfies the boundary condition of zero vertical velocity at the ground plane. Away from the ground plane, the downwash of the two trailing vortices contributes to the wing drag due to lift by rotating the force vector rearward. Near the ground plane, however, the trailing vortices of the image vortex system have an upwash component. The upwash component reduces the downward rotation of the flow caused by the wing trailing edge vortices, thus reducing induced drag, or wing drag due to lift. The classical treatment of this effect is given by Wieselsberger (Ref. 5.4-1). This approach was extended to consider the induced effects of the image bound vortex. (Ref. 5.4-12) Both of these approaches are summarized in Reference 5.4-13. The bound vortex of the image-vortex system reduces the longitudinal velocity component at the wing bound vortex thus modifying the circulation of the wing bound vortex. These effects, including a possible profile drag reduction, become more predominant as the height above the ground is reduced.

Theoretical analyses of ground proximity have been formulated by using lifting surface theory and, because of its general nature, computer programs have been generated to facilitate computations. More recently, numerous computational fluid dynamics codes have been developed which can be adapted to investigate the phenomena. A significant effort summarized by Ashill (Ref. 5.4-14) provides a method for calculating induced drag in ground effect as well as suggesting how induced drag formulations may be applied to wings with endplates. For performance calculations, these higher fidelity methods and the simpler methods agree well enough that either can be used.

5.4.1.3 Experimental Ground Effect Testing

Wind tunnel investigation of ground effect is approached, usually, using one of four testing techniques:

(1) Fixed Ground Plane
(2) Moving Belt Ground Plane
(3) Image Model with Respect to a Fictitious Ground
(4) Boundary Layer Removal from the Ground Board

The fixed ground plane technique is the most straight forward. However, this method does not give a true representation because of the lack of motion between the ground plane and the model. This lack of motion permits a boundary layer build-up which leads to higher than anticipated lift coefficients (Ref. 5.4-15), which may be due to reduction of the gap by the boundary layer displacement thickness. However, drag coefficient and pitching moment coefficient appear to be unaffected.

The moving ground belt eliminates this problem but is expensive to build, operate, and maintain. When small clearances are required, problems occur in maintaining a smooth belt surface under the model because of the difficulty of providing guides in the vicinity of the model.

The third technique, the image model method, has the disadvantage of cost since an additional model is required to be duplicated to simulate the mirror image of the test model but the procedure works well.

The fourth method involves controlling the ground board boundary layer, using a method of blowing or sucking through slots to replace the momentum lost by the boundary layer. The thickness of the boundary layer can, to some extent, be controlled by a flap on the trailing edge of the ground board although care must be taken here not to alter the circulation around the ground board. These methods are not commonly used owing to their complexity and cost. When a configuration nears finalization a moving ground board is used. As might be expected, results using different testing techniques yield somewhat different results for the same configuration. The lack of agreement between various wind tunnels as well as wind tunnel versus limited flight test results is shown in References 5.4-16 and 5.4-17. This is consistent with Russian experience.

5.4.1.4 Lift In Ground Effect

The unique feature of flying close to a surface is usually (but not always) an increase in lift for a given angle of attack. Reference 5.4-18 discusses the effects of angle attack in ground effect. The effect of the ground, usually, is to increase the lift curve slope and decrease the angle of attack for a given lift. Ground effect may decrease the maximum C_L available and this characteristic is primarily a function of planform. Ground effect may also reduce the C_L available at low angles of attack. Reference 5.4-7 shows that the maximum C_L in free air is a function of aspect ratio, taper ratio and thickness chord ratio. If endplates are fitted the C_{Lmax} may decrease slightly. Reference 5.4-7 suggests that OGE (Out of Ground Effect) C_{Lmax}'s for wings without flaps varying in aspect ratio from 1.0 to 4.0 may vary from 0.9 to 1.2 with 1.4 being achieved by an Aspect Ratio 2.0 tapered wing. In ground effect (IGE) for the same set of wings, Reference 5.4-7 shows a C_{Lmax} of about 1.6 independent of aspect ratio with a flap deflection of 15 degrees. The ORLYONOK based on the demonstration achieved a lift-off C_L of approximately 1.33 with injected air in use. Both Russian literature (Ref. 5.4.9) and statements by Russian engineers say that injected air reduces the takeoff speed by 8 to 11% corresponding to an increase in lift coefficient of 18 to 26%. The parametric study of this report assumed similar values of C_{Lmax}. The calculated C_L at lift off based on discussions for the LUN/SPASATEL is 1.25. This compares to takeoff lift coefficients of about two for highly developed transport wings with double fowler flaps.

Reference 5.4-9 shows the pressure distribution on a rectangular, aspect ratio 2, wing-in-ground-effect. Of interest is that as the ground is approached the velocity and, therefore, the lift of the top surface is reduced. However, this is not the case for delta wings. As the ground is approached the velocity increases on the upper surface and the overall effect is that the delta wing sees a greater augmentation of lift in ground effect (Ref. 5.4-19). In addition, flight experience shows ground effect is much more noticeable on delta wings at low angles of attack (Ref. 5.4-20).

5.4.1.5 Drag In Ground Effect

The primary benefit of flight in ground effect is a reduction in induced drag. To estimate the drag associated with lift in surface effect to support the parametric analysis, five theories were compared. Figures 5.4.1-2 and 5.4.1-3 show the comparison with and without endplates, respectively, with the data from Reference 5.4-7. The total drag coefficient (C_{Dt}) is the sum of the profile drag coefficient (C_{Do}) and the induced drag coefficient (C_{Di}). C_{Do} was obtained from the wind tunnel results and C_{Di} was estimated using the methods described in References 5.4-1,

5.4-14, 5.4-21, 5.4-22, & 5.4-23. The expressions presented in the references, except for Reference 5.4-14, were derived for wings without endplates. However, it was noted by Gallington (Ref. 5.4-24) that with the introduction of endplates to a wing configuration, the tip vortex was displaced to and shed from the bottom of the endplate. Therefore, the bottom of the endplate rather than the trailing edge height is the controlling height for all the methods considered when the wing is equipped with endplates. This was further confirmed by Ashill's work in Reference 5.4-14 and his unpublished thesis. Thus for wings with endplates the methods for the previously cited references were used but the reference height was taken as the height from the ground board to the bottom of the endplate at the trailing edge of the wing.

Figures 5.4.1-2 and 5.4.1-3 show Wieselsberger's theory is the most optimistic. However, in the parametric analysis an Oswald Efficiency of 0.85 was used which is lower than that achieved by the lower aspect ratio wings tested by Lockheed. Assuming no adverse interference by the fuselage the difference in the Oswald Efficiency compensates for the optimism of the Wieselsberger theory when compared to the wind tunnel results reported in Reference 5.4-7. In comparing Wieselsberger's theory with the Lockheed results for all wings tested, Wieselsberger's theory proved optimistic in terms of reduction in induced drag.

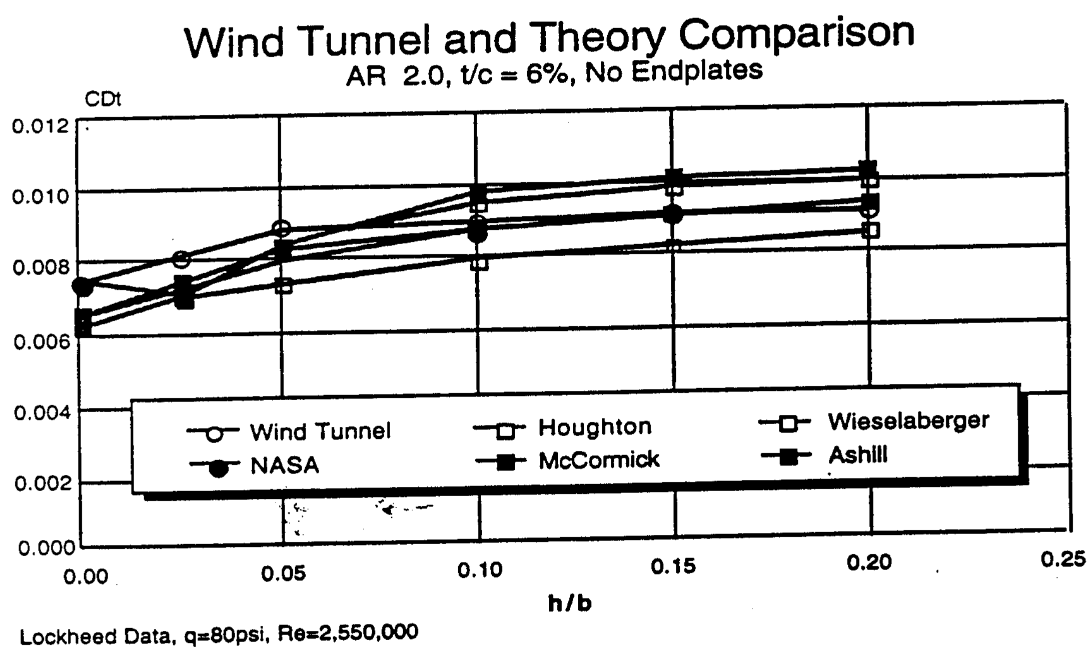

Figure 5.4.1-2
C_{Dt} versus h/b (with endplates)

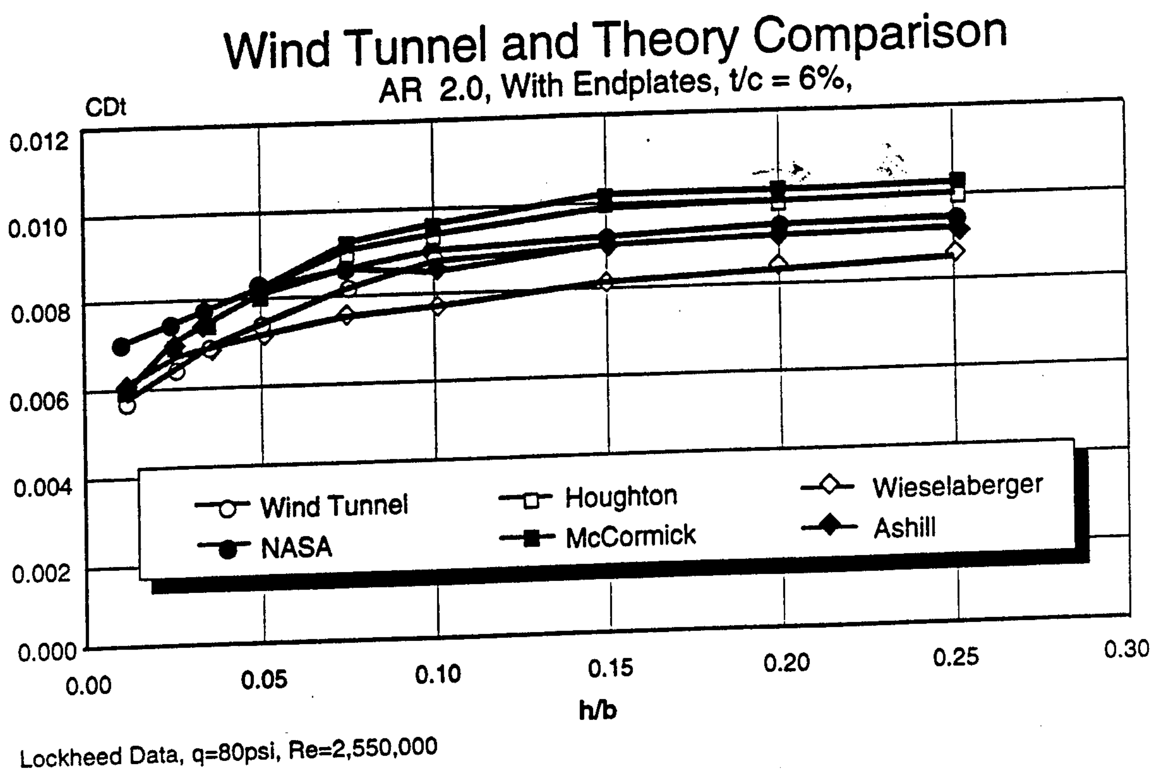

Figure 5.4.1-3
C_{Dt} versus h/b (no endplates)

However, none of the other theories consistently matched the Lockheed results. Therefore, a wind tunnel-established Oswald efficiency, along with a theory supported by data which represents the closest analogue in terms of wing section, planform and endplate configuration, is appropriate for estimating induced drag in ground effect where wind tunnel results are not available in ground effect for the configuration under consideration.

Discussions with Russian scientists and engineers pointed to a possible reduction in profile drag in ground effect. Reference 5.4-25 suggests a reduction in wing profile drag of 16% at 0.2 h/c (trailing edge height/geometric average chord) while Reference 5.4-26 shows a profile drag reduction to be a function of lift coefficient. The reduction in wing profile drag was shown to be of the same order, 13 - 15%, as that given in Reference 5.4-25. However, no evidence of such a trend was evident at the lift coefficients analyzed in the Lockheed data. The reduction in total drag attributable to reduction in profile drag is at most 4% because wing profile drag is about one-quarter the total drag.

The possibility of laminar flow on the underside of the wing was also mentioned to the Russians. This possibility was first suggested in Reference 5.4-27. A recent investigation (Ref. 5.4-28) using the MIT ISES code shows the likelihood of laminar flow, especially for relatively thin symmetrical section wings, of the order of 5% in ground effect. The Russians have continually stressed the importance of using thinner wings as the ground is approached without providing a reason. We believe the reason is for better height stability. They have also admitted that TsAGI is investigating the possibility of extending the amount of laminar flow on wings in ground effect. Generally speaking transition occurs at about a Reynolds number of 1,000,000 and the modelling done in Reference 5.4-28 was for a Reynolds number of 30 million. Full scale wing Reynolds numbers will approach Reynolds numbers of around 500 million. Roughness also impacts transition from laminar to turbulent flow. At sea level the limits of roughness are such that the surface finish must be much better (smooth and devoid of even the smallest waves) than at altitude. For example, at 50,000 ft and Mach 1.0 the tolerable roughness is the same as for a flight Mach number of 0.17 at sea level (Ref. 5.4-29). This suggests, at sea level, laminar flow may be difficult to achieve and perhaps maintain.

Finally, discussions with Dr. P. R. Ashill confirmed the possibility of reducing drag by designing endplates to exhibit leading edge suction. This improvement may be incompatible with the hydrodynamic shaping requirements on endplates. The possibility of a reduction in form drag in ground effect was suggested. Also, small wing camber changes were noted to make significant increases in L/D as noted in the wind tunnel tests reported in Reference 5.4-30.

During the study, concerns were voiced about achieving a low C_{Dt} needed for long range, at extremely high Reynolds numbers. At very high Reynolds numbers, of the order 500 million representative of a wing chord of 150 ft, the reduction in skin friction coefficient with Reynolds number may not be maintained if the roughness on the wing is equal to 1/3 the boundary layer displacement thickness.

Reference 5.4-31 discusses profile drag issues on subsonic aircraft. It reinforces the point previously made that even if the boundary layer is turbulent everywhere, the skin friction drag is dependent on the uniform roughness. Beyond a critical Reynolds number based on mean roughness height, the skin friction rises above the value predicted for a smooth surface instead of progressively decreasing with increasing Reynolds number. There is a tendency for it to remain constant with Reynolds number. Reference 5.4-30 also shows that a delta wing aircraft can have much less incidental profile drag than other configurations.

Areas that need significant attention during the design and development of aircraft and therefore of large WIGs include:

(i) excrescences, surface imperfections, roughness etc., items which typically at present contribute drag increments amounting to 15 - 24% of the estimated profile drag (but only 8% in one case),

(ii) Mach number effects at C_L cruise between low Mach number and M cruise which typically contribute about 10% (but only 5% in two cases), and

(iii) nacelle interference which, even at low Mach number can contribute 40 - 80% of the estimated nacelle profile drag.

To these can be added wing body interference for medium to low wing layouts and rear fuselage drag. To insure that the profile drag is not affected in an adverse manner, a procedure can be implemented that establishes drag budgets and surface finish standards (step heights, gap widths, skin waviness, paint smoothness, flush rivet head protrusion limits) as a function of aircraft zone as determined by a C_p (Pressure Coefficient) survey of the complete aircraft at representative cruise lift coefficients and boundary layer momentum surveys (shows how the skin friction coefficient is varying) over critical areas of the configuration.

In summary, the drag prediction of a complete configuration still has its uncertainties. However, in ground effect, there appears to be the opportunity of reducing the profile drag through judicious use of advanced analysis and design techniques for future WIG configurations.

5.4.1.6 Moment And Trim

As mentioned above, the unique feature of flying close to a surface is the general increase in lift. The increase in lift is generally accompanied by an increase in magnitude of the normally negative (nose down) pitching moment coefficient. With landplanes this becomes a design condition for setting the area of the horizontal stabilizer. Thus if natural stability is to be required the horizontal stabilizer must provide the natural stability and the ability to trim the platform in all flight and takeoff and landing conditions. In the takeoff and landing conditions trim may be provided through additional means.

For a water-based WIG of conventional airplane configuration, the horizontal stabilizer must be larger in order to accommodate the greater pitching moment coefficients (neglecting hydrodynamic moments) experienced during takeoff and landing when the wing is in strong surface effect and during cruise flight to achieve adequate longitudinal stability. The increase in size of the horizontal stabilizer over a conventional aircraft for the same moment arm with conventional wing planforms will be range between 25 and 80% based on data in Reference 5.4-7 depending on wing aspect ratio and allowable fuselage pitch angles for takeoff and landing. This increase in horizontal stabilizer size increases both drag and structural weight fraction but could be somewhat reduced by limiting the c.g. travel or eliminated by the use of new innovative control concepts.

In cruise, the cruise height can have a significant impact on trim drag owing to the variation of pitching moment coefficient with height above the surface. From the discussions with the Russians no obvious concern was shown, perhaps, because the Russian WIGs are primarily short range vehicles. Reference 5.4-30 showed a reduction of 42% in cruise L/D owing to trimming out the pitching moment for a WIG with an aspect ratio of 0.5 using augmented endplates. Approaches to reduce the trim drag include fuel transfer to optimize c.g location, and/or using a combination of more sophisticated wing planforms, wing sections and new innovative control concepts.

5.4.2 Stability And Control

The basic operating mode of wingships is relatively high speed flight, preferably in excess of 200 knots, at an altitude equal to 10-30 percent of the wing mean aerodynamic chord. While there have been many different types of WIG vehicles envisioned for high-speed, over-water transportation in different countries, the wingship configuration that has reached the highest level of technical maturity is the Russian "ekranoplan." This configuration includes the "power augmented ram," or PAR concept, and may have capability for out-of-ground-effect flight. The stability and control of wingships has been analyzed by several investigators during the past 25 years. One of the earliest (1967), and most complete analyses of the dynamics of wingship motion was performed by Kumar (Ref. 5.4.2-1). A thorough review of early Soviet efforts was performed by Hooker (Ref. 5.4.2-2). Some of the analyses by Russian authors, such as Vachasov and Kurochka (Ref. 5.4.2-3) and Irodov (Ref. 5.4.2-4), employed simplifying assumptions that led to such incorrect conclusions that for longitudinal stability, the center of gravity of wingships must lie behind the

trailing edge of the mean aerodynamic chord. All of these analyses made use of the equations of motion that were linearized about a trimmed, straight and level flight path, although Staufenbiel (Ref. 5.4.2-5) retained some nonlinear terms.

In contrast with stability analyses, the published literature on handling qualities and control system implementation of wingships is relatively scarce. Two notable exceptions are the volume entitled, Wingship Compendium (Ref. 5.4.2-6), and a paper by Diomidov (Ref. 5.4.2-7) acquired from the author by the WTET during its recent visit to Russia. In the Wingship Compendium the actual implementations of the control systems of two large Russian wingships, that of the 140-metric ton ORLYONOK and of the 450-metric ton LUN, are described. In Reference 5.4.2-7 the design and development of the autopilots for the ORLYONOK and LUN is presented.

In the following paragraphs the state-of-the-art of wingship stability and control and the more important technical issues related to handling qualities and control system implementation will be discussed in additional detail.

In the dynamics of airplanes two kinds of stability are of interest. The first of these is static stability which means that when the vehicle is disturbed from its equilibrium, it will tend to return to the state of equilibrium. The second kind, dynamic stability, is more complicated; it basically means that following a disturbance, an underdamped vehicle will oscillate about the state of equilibrium, but eventually the oscillations will die out and the vehicle returns to its steady, equilibrium state. The conditions for static stability of a wingship in cruising flight are more restrictive than those of conventional airplanes. In the longitudinal axes, the derivative of the pitching moment with respect to angle of attack must be negative, and the derivative of the power required with respect to airspeed must be positive. For wingships these conditions are augmented by the requirement that the derivative of the lift coefficient with respect to altitude must be negative. The latter condition expresses the requirement for altitude, or heave stability. In the lateral-directional axes, the conditions for static stability are that the derivative of the rolling moment with respect to sideslip be negative, and the derivative of the yawing moment with respect to sideslip be positive. These conditions are identical to the requirements for dihedral and weathercock stability of conventional airplanes. For wingships there is the additional requirement that the derivative of rolling moment with respect to roll attitude be negative.

When it comes to expressing the necessary and sufficient conditions for dynamic stability, the published literature to date on wingship stability relies on the Routh-Hurwitz criterion, which states that the roots of the characteristic equation must have negative real parts for stable dynamic

behavior. That is, the designers are seeking a machine that is naturally stable. The fact that none of the more recent methods of linear system analysis has been utilized to express the conditions for dynamic stability stems from the fact that only the two large Russian wingships utilize feedback control for artificial dynamic stability. Before dealing with the control problems of these vehicles, the reader should note that the equations of motion of wingships require the simultaneous solution of a kinematic equation along with the usual dynamic equations. These equations are normally ignored for conventional airplane stability investigations. Since for wingships the forces and moments depend on both altitude and roll angle, the differential equations for these quantities must be appended to the usual equations of rigid body dynamics. The extra kinematic equations give rise to the increased, i.e. fifth order of the characteristic equations for both the longitudinal and lateral-directional axes.

The requirement of height stability for wingships has resulted in configurations that differ somewhat from the layout of conventional airplanes. Staufenbiel shows that for positive height stability the horizontal tail should be out of ground effect and the horizontal tail volume should be large. (Ref. 5.4.2-8) These characteristics are obviously apparent on the large Russian wingships, the ORLYONOK and the LUN.

There is no operational experience in the United States with wingships of any size; however, in the opinion of several highly experienced NASA test pilots manual control of a wingship over extended periods of time would be a very demanding task even in benign weather and day-time conditions. Verbal contacts with the Russian wingship technical community confirmed the opinion of the American pilots. Analytical results relying on wind tunnel data on a relatively small wingship (Ref. 5.4.2-8) show that at intermediate heights while transitioning between free flight and flight in ground effect the long-period, phugoid-like motion of the wingship is slightly unstable, and cannot be trimmed for steady, equilibrium flight. Another analytical study (Ref. 5.4.2-9) into the effect of wind shear on the longitudinal stability of conventional airplanes shows that the phugoid mode can be destabilized in wind shear, depending on the direction of the wind. Since in windy weather wingships fly in the planetary boundary layer with wind shear, one would expect that the wingship long period motion would be similarly affected. For these reasons it is generally agreed that wingships could be utilized for extended flights in ground effect only if they possessed stick-free stability.

For the technology area of providing artificial dynamic stability for wingships, the visit of the WTET to Russia proved to be very valuable. The Russian experience with what they term as "automatic motion control system" or AMCS is described by Diomidov (Ref. 5.4.2-7). It is clear that the requirement for artificial stabilization was realized and established by the Russian wingship designers as early as 1964. Both the ORLYONOK and the LUN are equipped by AMCS which

were designed by the Central Research and Development Institute "Electropribor." The total flight time accumulated by these systems is reported to be 1,500 hours. The designers of these systems borrowed freely from the experience of avionics systems in the former Soviet Union, but they faced some problems unique to wingship operation, such as the transition between flying in and out of ground effect. According to Diomidov, the AMCS provides the following functions in the ORLYONOK wingship:

- Pitch, roll, yaw, and altitude damping
- Altitude, pitch and roll attitude and heading "Hold"
- Altitude, pitch attitude "Select"
- Altitude, sinking speed, and wave height estimation
- Cockpit displays
- Envelope limit warning
- Aerodynamic surface trimming
- Redundancy management/failure annunciation

A more advanced version of the AMCS, installed in the LUN wingship, provides all of the above functions, plus the following:

- Air speed "Hold" and "Select"
- Envelope limiting
- Aerodynamic surface coordination
- Fly-by-wire control of the PAR nozzles
- Altitude change predictor

The actual mechanization and the level of redundancy of the AMCS was not specified by Diomidov; however, there were good indications that the designers of these systems utilized both elevator and active flap control, the latter in the fashion of direct lift control for conventional fighter type airplanes. The available information on the hydro-mechanical components of both types of wingships shows them to be identical to the fully powered controls utilized on conventional airplanes of comparable size.

Russian automatic flight control systems designers indicated that the next generation of these systems should be a digital computer based, fly-by-wire mechanization, following the trend established for western avionics systems during the last decade. Such mechanization would allow the automation of takeoff and landing, steep trajectories in and out of ground effect, terrain avoidance, and advanced electronic cockpit displays. None of these functions are yet found on any

of the Russian wingships, but, according to Diomidov, they would free wingship designers to concentrate on configurations with greater aerodynamic efficiency and operating economy.

The amount of information on wingship operation until recently has been very meager, even though the first flight of the Soviet KM, or the Caspian Sea Monster, took place over twenty years ago. According to the information gathered by the WTET in the course of three separate visits to Russia earlier this year, only the wingships ORLYONOK and LUN have been turned over to the Soviet navy, and the use of both types were apparently confined to the Caspian Sea. Since the breakup of the Soviet Union neither type has flown with the exception of an ORLYONOK with tail number 26. The latter vehicle was used as a demonstrator to the WTET during its recent trip to the Caspian Sea. The other type of wingship that was also demonstrated during the first two Russian visits of the WTET (to the CHDB in Nizhny Novgorod) is the small, two-men "Strizh." Although a considerable amount of information has recently been made available by the Russians on wingship operations, we remain unsure of the sustained out-of-ground-effect capability of the Russian wingships. During the flights we observed, both the Strizh and the ORLYONOK stayed within 30 feet of the surface and were out of ground effect for only a few seconds.

The Russian designers of the ORLYONOK and LUN stated that the design envelopes of these two vehicles had been completely cleared. No adverse weather or night operations to date have been conducted, although wind limits of 20 m/sec with a cross wind component of up to 5 m/sec have been established. Turn rates of the larger wingships are in the neighborhood of 2.5 deg/sec; the Strizh can probably turn faster because of its lower cruise speed. Since both the altitude and the wave height are critical measurements not only for height stability and aerodynamic performance, but also for flight safety, an attempt was made during the WTET Russian visits to determine how these parameters are measured on the large Russian wingships. According to Viktor Sokolov, the general director of the CHDB, three measurement techniques are used, the preferred one being radar altimetry. The location of the Doppler radar receivers and transmitters on the wingship ORLYONOK is shown in the accompanying Figure 5.4.2-1. The other two techniques involve sonar devices and the measurement of the earth's electric field strength by ionizing the air with small samples of radium. The ionized air in the vicinity of the radioactive material allows the

measurement of the potential associated with the electric field of the earth. (See Ref. 5.4.2-10) Since the latter is a function of altitude this technique can be used for the determination of altitude or aircraft attitude if multiple radioactive probes are used.

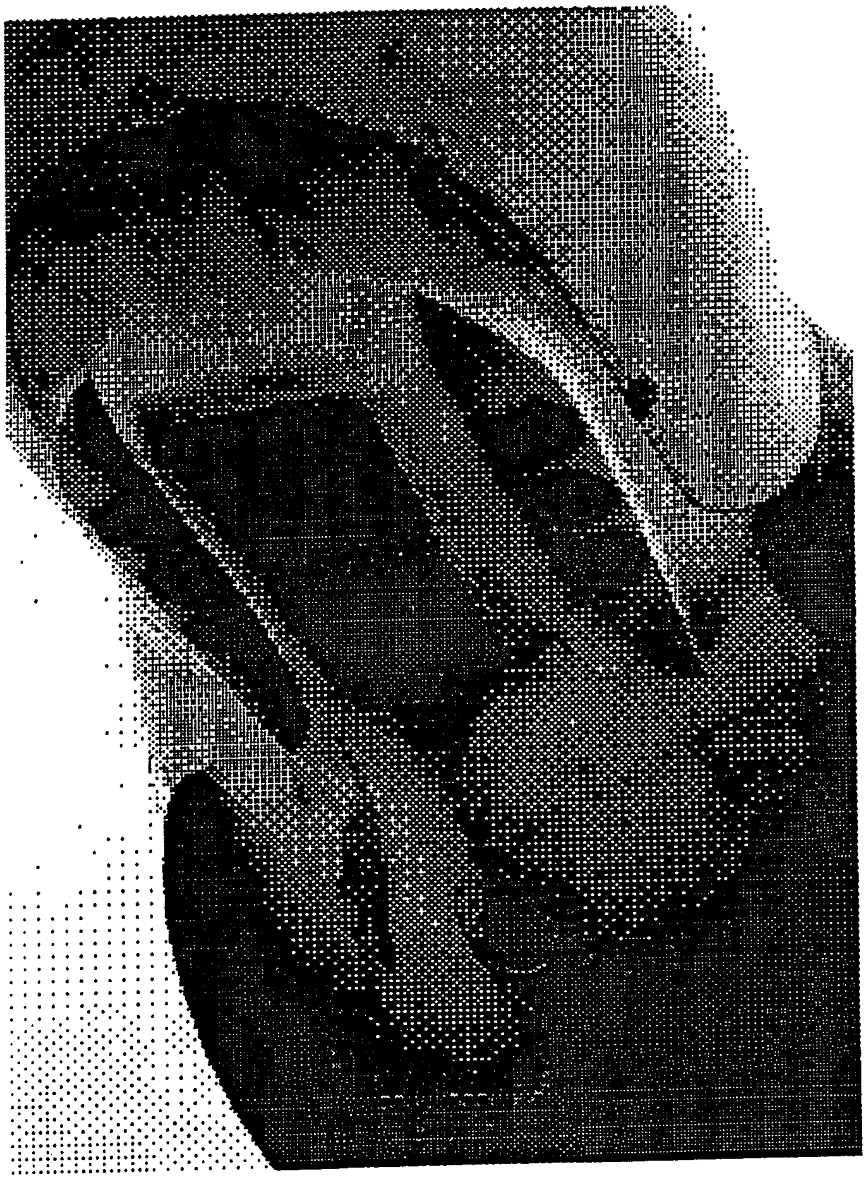

Figure 5.4.2-1
Location of Doppler radar transmitters and receivers on the Orlyonok

This section of the final report of the WTET on wingship stability and control may be summarized by stating that the feasibility of the wingship concept up to an approximately one million pound takeoff weight has been demonstrated in the former Soviet Union during their wingship development spanning the past thirty years. In the area of stability and control the current state-of-the-art is at a point where the technical risks are minimal. Those areas of flight controls technology, such as digital fly-by-wire controls, terrain avoidance, and automatic takeoffs and landings, which have not yet been utilized in Russia, are well within the state-of-the-art in this country. In the application of advanced flight control techniques, however, there is heavy reliance on the mathematical model of the vehicle to be controlled. The mathematical modeling, including subscale testing of wingships to generate the necessary static and dynamic wind tunnel data, and simulation studies into the maneuvering capabilities of wingships, appears to be an area where future cooperative efforts with the Russians might prove to be beneficial.

5.4.3 Hydrodynamics

Although discussions of wingship performance usually concentrate on the cruise condition, when the craft is flying above the water surface and PAR is not applied, a more critical design condition is the takeoff run where PAR is operational and hydrodynamic forces on the vehicle are substantial. Typically, the thrust required during takeoff may be 2-3 times the cruise thrust. Further, since the hull, wing flaps, end plates, etc., are in contact with the water, their geometries are driven by hydrodynamic considerations which usually are in conflict with the low drag aerodynamic geometries required in the cruise condition. In addition, wingships must land and takeoff in waves; hull structure designs capable of withstanding the concomitant hydrodynamic input loads result in relatively large structural weight fractions.

Unfortunately, because of the complexity of the aerodynamic/hydrodynamic processes encountered during takeoff and landing, there is a paucity of analytical tools to assist the designer. Consequently hydrodynamic model tests are relied upon heavily to define the water-borne and landing and takeoff characteristics of wingships.

A typical takeoff flight sequence for the 350 ton Russian wingship LUN as described by the Russians during the WTET meeting (See Trip Report-Appendix G) with CHDB in Nizhny Novgorod is:

Speed % takeoff	Wing Flap Deflection	PAR Nozzle Deflection	Thrust
0- 10	0°	0°	20% max
10- 30	0°	20°	max
30- 45	10°	20°	max
45- 60	15°	20°	max
60-100	20°	20°	max

cruise = 1.5 takeoff

It is evident that flap deflection is programmed to increase as speed is increased and the hull is gradually lifted by aerodynamic forces to reduce the draft of the hull. This is to avoid large hydrodynamic loads on the flap where the draft of the hull is still large. Since the takeoff speed (340 km/hr) is approximately 65% of the cruise speed (500 km/hr) (at least for the LUN), the hull will remain in contact with the water surface for a wide speed range despite activation of the PAR system.

Earlier U.S. tests showed that the PAR mechanism can sustain lift at low speed; i.e. during takeoff and landing (Ref. 5.4.3-1). Why Russian design did not exploit this potential is not clear. With the craft expected to ride out of the water at low speeds, hydrodynamic loads at takeoff and wave impact loads during landing were expected to be reduced substantially. Perhaps future wingship designs will have such a low speed lift capability but for the present it is prudent to design hull forms which will remain in contact with the water from low speed displacement mode to high speed planing mode.

Hydrodynamically Compatible Hull Form The water-borne requirements of a wingship hull are not dissimilar to those of a seaplane hull and indeed, the Russian ORLYONOK (Figure 5.4.3-1) incorporates many seaplane characteristics. The principal geometric features are:

- Upswept buttock lines in the bow to provide the ability to ride up the flanks of waves at low speed and thus reduce wetting of the bow and windshield and especially to reduce flow of green water into the jet intakes.

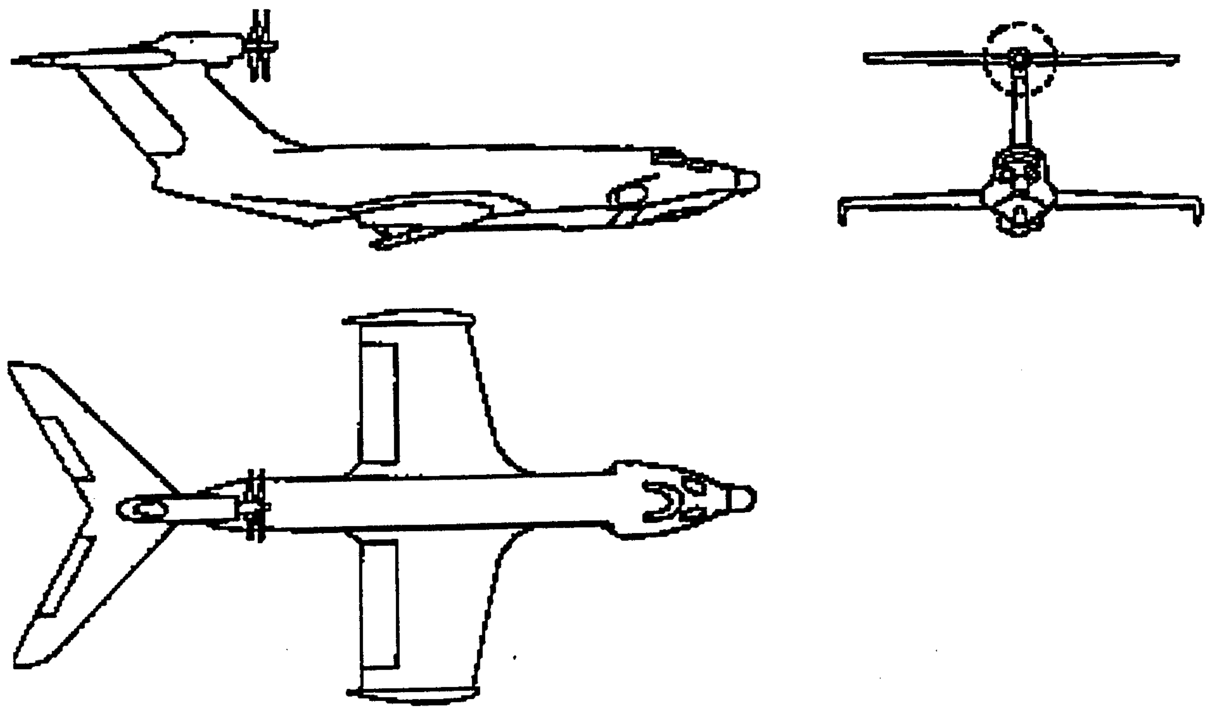

Figure 5.4.3-1
The Russian Orlyonok

- The use of hard chines to provide flow separation from the bottom and to avoid wetting the sides of the hull.
- Incorporation of large spray deflectors at critical locations along the chine.
- Use of transverse steps on the hull and wing end plates to reduce their wetted surface.
- Avoidance of convex surfaces on the aft portions of the forebody and the afterbody to avoid suction in the planing range.
- Incorporation of deadrise angle, double chine, or hydroski on the forebody to reduce wave impact loads.

These geometric features will increase the aerodynamic profile drag of the vehicle but are necessary to assure acceptable hydrodynamic performance. If the PAR system can be designed to lift the hull at low speed, then these hydrodynamically driven geometries can be relieved.

Total Resistance During Takeoff in Calm Water. Both hydrodynamic and aerodynamic forces are involved in the behavior of a wingship during takeoff. The primary aerodynamic forces are wing lift, drag and moment due to PAR and forward speed, thrust and moment, and horizontal tail force and moment. The aerodynamic lift forces increase with speed and hence reduce the load on the water as speed is increased. As the hull rises with forward speed the beneficial ground effects on PAR performance, wing lift and drag, are reduced.

The primary hydrodynamic forces during takeoff are hull drag (both form and viscous); drag on wing, wing flaps and wing end plates due to impact with hull and PAR generated spray and wake (which TsAGI estimates to be a major hydrodynamic drag component); drag of surface-piercing end plates; and wave-making drag of PAR cushion. These resistance components are dependent upon hull draft and trim which vary with speed and the aerodynamic characteristics of the PAR wingship.

The published literature contains many references for estimating the aerodynamic drag components and Reeves (Ref. 5.4.3-1) presents detailed calculations for a 5,000 ton wingship in the cruise condition. Similar methods may be used for the takeoff condition.

There are few analytical methods for reliably estimating the hydrodynamic drag components. Such critical items as hull lift and center of pressure from zero speed to takeoff speed (from fully buoyant support to planing support) are still in the process of development. When combined with PAR, wing, and tail aerodynamics, they establish the equilibrium draft, trim, and resistance of the hull as a function of speed. The orientation of the hull governs the geometry and intensity of the spray which, upon striking the wing, flaps, or end plates can produce large drag forces. To avoid large hydrodynamic forces on the flaps they are programmed to be incrementally extended as the hull rises with increasing speed. For the same reason, the Beriev A-40 seaplane extends its flaps only when speeds exceed 50 knots on the water. In addition to spray forces on the flap they are also subject to hydrodynamic forces when running into the hull generated waves. Aerodynamic drag penalties may partially or completely cancel the improved PAR performance caused by flap deflection. At this time, analytical methods for estimating these spray and wake induced forces are not developed.

Large hydrodynamic drag forces are developed by the end plates throughout the takeoff speed range. Gallington (Ref. 5.4.3-2) presents a method for estimating the forces on end plates

penetrating waves and discusses limits on yaw angle and speed. Savitsky and Breslin (Ref. 5.4.3-3) and Chapman (Ref. 5.4.3-4) present methods for estimating the spray drag of surface-piercing end plates. The effect of the impact of the endplate generated spray onto the wing and flaps is not yet quantified.

The wave-making drag of the PAR and wing-generated air cushion may be estimated using Doctors (Ref. 5.4.3-5). For high length beam ratio pressure patches, ($L/b = 6$) the maximum value of wave-making drag is approximately 1-2% of gross weight and occurs at a Froude number, $F_L = V\sqrt{gL}$, equal to approximately 0.80. It increases as the square of the weight and as the length-beam ratio of the pressure patch is reduced.

Hydrodynamic instabilities, resulting in porpoising, may occur during takeoff. Currently, model test are the most reliable way to study porpoising.

Use of Model Tests. Because of the uncertain hydrodynamic/aerodynamic effects and interactions, the takeoff characteristics of wingships are best defined by model tests in towing tanks. The Russians have made extensive use of a variety of hydrodynamic test facilities during the development of all their wingships.

To provide some guidance as to the variation of total resistance with speed during takeoff, model tests of an ORLYONOK type wingship are shown in Figure 5.4.3-2. It is seen that, at zero speed, the resistance is approximately 8% of the craft weight when the PAR engines are developing maximum thrust. The drag increases as speed is increased and attains a maximum value of approximately 17% of the craft weight at hump speed ($\Delta_0/D = 6.0$). It is noted that both the PAR engines and cruise engines are required for takeoff. Further because of the large drag increment due to PAR, the excess thrust (relative to drag) is reduced at pre-hump speed resulting in long takeoff runs. It is interesting to note that the Russians (Dr. Sokolov and Prof. Logvinovich) essentially confirmed the U.S. estimated drag-lift ratio during takeoff. The weight-drag ratio (Δ_0/D) at cruise is estimated to be 18 which is nearly three times greater than that at hump speed. This demonstrates the dominance of hydrodynamics in the selection of the propulsion system.

The takeoff resistance of a modern high length beam seaplane model is presented in Figure 5.4.3-3 (Ref. 5.4.3-6). The hump resistance is approximately 18% of the gross weight

CRDKNSWC/RD-22-93/98 (March 1993)
CRDKNSWC/RD-22-93/99 (April 1993)
(Trim Angle Fixed at 0°)

Δ_o = 38.5 lbs Scale = 20

D_T = Aero + Hydro Drag
T_P = Par Engine Thrust = 6.28 lbs
T_C = Cruise Engine Thrust = 3.50 lbs

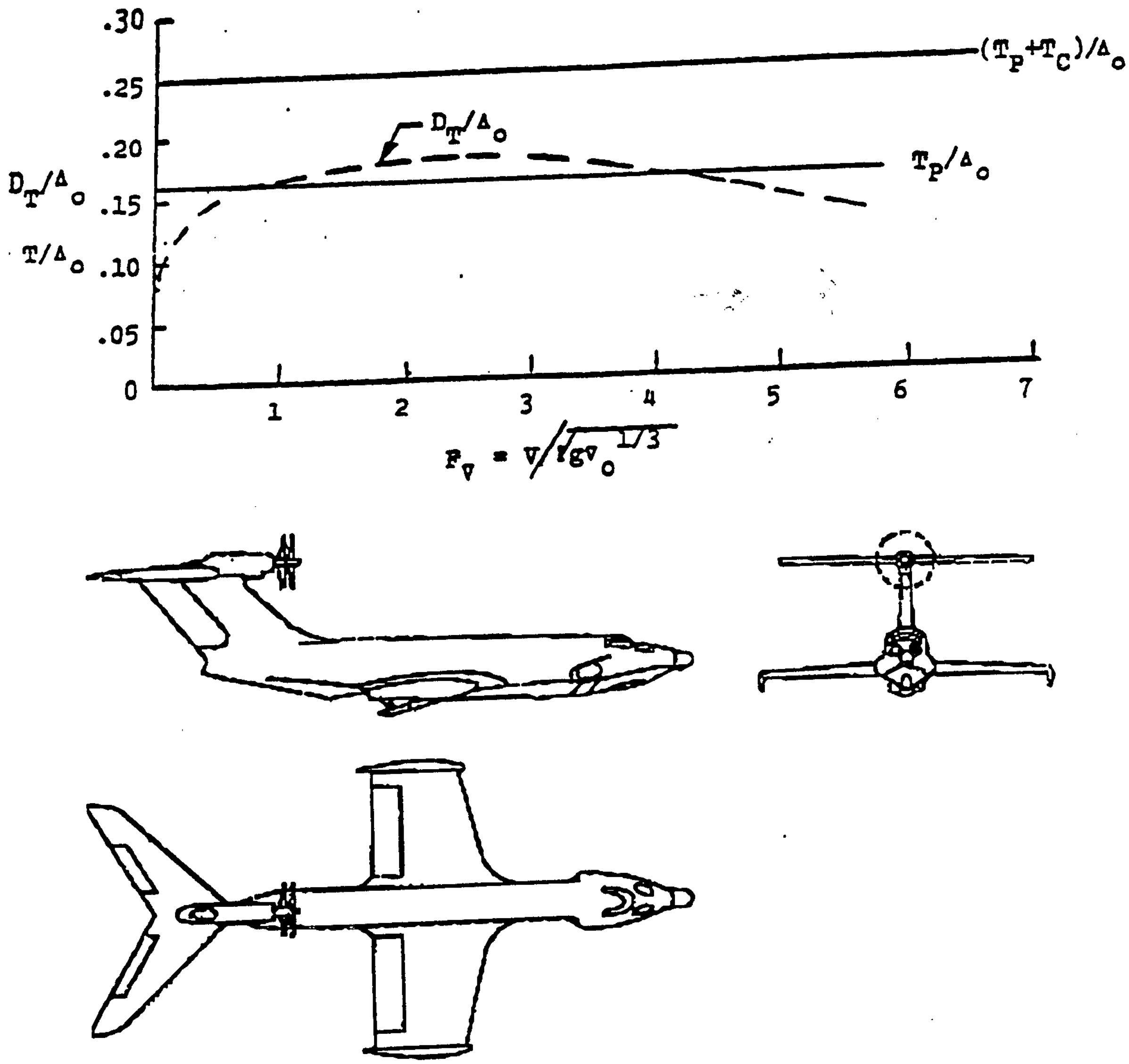

Figure 5.4.3-2 Orlyonok-WIG

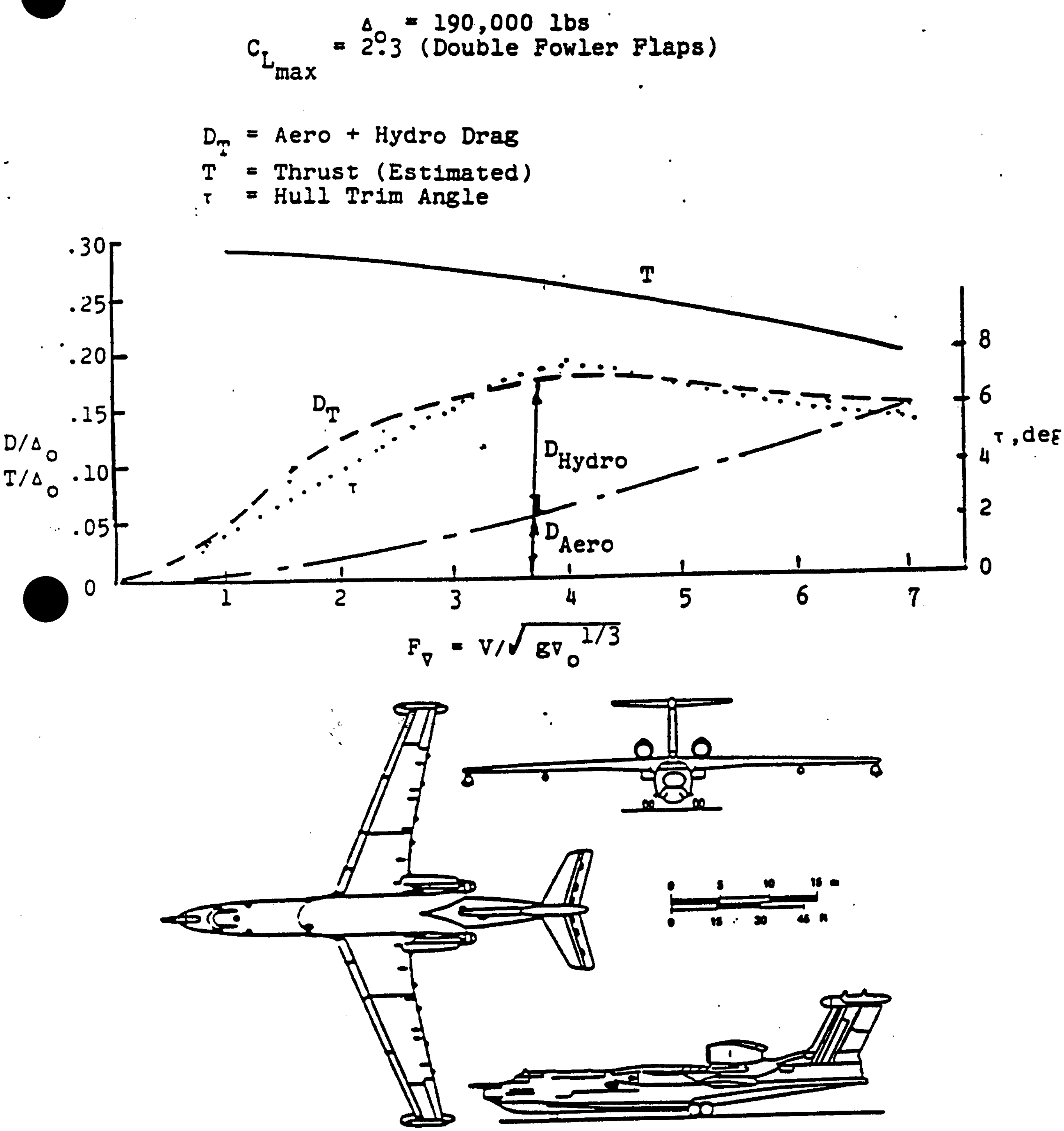

Figure 5.4.3-3. Albatross Type Seaplane

(essentially similar to the ORLYONOK). Further, the large excess thrust in the early stages of takeoff provides for rapid acceleration of the seaplane. As a further comparison, we were informed by the Russians that their A-40 seaplane has a takeoff speed of approximately 200 km/hr compared to 340 km/hr for the LUN wingship.

5.4.4 Operation In Wave Environment

A key design consideration for large WIG ships is the ability to operate as a transoceanic vessel in a variety of sea states. Figure 5.4.4-1 indicates the range and frequency of occurrence of sea conditions in an open ocean environment.

There are several major considerations stemming from operating in a sea state. These are:

- Floating and drifting in waves
- Takeoff in waves
- Landing in waves
- Cruise flight over waves
- Occasional impact with rogue waves in the cruise condition

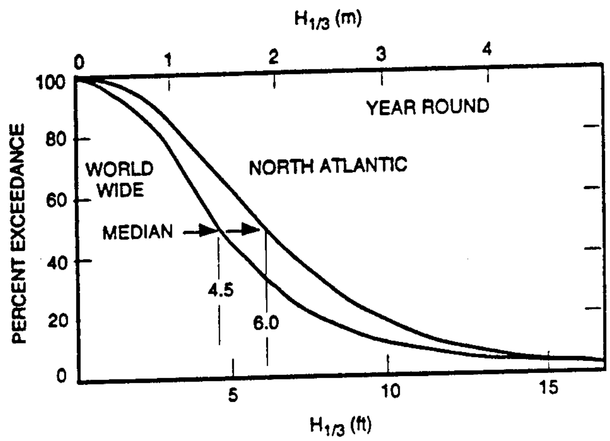

Figure 5.4.4-1
Expected Occurrence of Sea Conditions

The principal consequences of a sea environment are: a reduction in lift-drag ratio as the craft flies further from the level water line to avoid wave contact and the development of large impact loads when the vehicle must land in waves.

5.4.4.1 Description Of Sea State

The annual sea state occurrences in the northern hemisphere are shown in Figure 5.4.4.1-1 where the sea state number is correlated with the significant wave height; sustained wind speed; probability of occurrence; and modal wave period. The weight height statistics for sea states are follows:

Average Height = H_{av}

Average of 1/2 Highest = $H_{1/2} = 1.41\ H_{av}$

Significant Height = Average 1/3 Highest = $H_{1/3}$ = 1.63 H_{av}
Average of 1/10 Highest = $H_{1/10}$ = 2.03 H_{av}
Average of 1/30 Highest = $H_{1/30}$ = 2.50 H_{av}
Average of 1/1000 Highest = $H_{1/1000}$ = 3.16 H_{av}

The Russians use $H_{1/30}$ to identify operating wave height. The U.S. and most other western countries use $H_{1/3}$ to identify the operating wave height. Thus, when discussing sea state capabilities, it is important to remember that:

$$H_{1/3} = 0.65\ H_{1/30}$$

An additional concern related to wave environment is the appearance of large ocean waves (rogue waves) which have been observed during storms in several locations of the world. Wave heights up to 200 ft have been observed in some areas. The large waves are a combination of large swells (up to 40 ft) and large waves of other storm systems (either local or from a large distance). Many ships have been lost in the Atlantic and Pacific when encountering fast traveling large waves which appear with little warning.

Rogue waves can build up within 12 to 24 hours to wave heights from about three times the normal significant wave height of a certain sea state in a storm up to a wave height of 100 feet, and 200 feet in extreme cases. Such waves are a combination of large swells and large waves of the same storm system or two different storm systems. The energy spectrum of these extremely large waves is simply the sum of the spectra of the swells and the superimposed waves.

5.4.4.2 Floating And Drifting In Waves

Several potential wingship missions require loitering in a seaway. This requirement has habitability and structural implications.

The sizes, proportions, and relative position of the hull, wings, and end plates greatly influence habitability. The ISO has established habitability standards for human performance, and these standards obviously apply to wingships which loiter on the sea surface. For example, Figure 5.4.4.2-1 shows the ISO habitability standard for heave acceleration (Ref. 5.4.4.2-1). A comprehensive design procedure for missions requiring sea-sitting must consider these standards.

ITTC87

Lee W T, Bales W L, Sowby S E
Standardized Wind and Wave Environments
for North Pacific Ocean Areas
R/SPD-0919-02 DTNSRDC Jul 1985

Sea State No.	Significant Wave Height (m)		Sustained Wind Speed (knots)*		North Atlantic			North Pacific			Northern Hemisphere		
					% Prob of Sea State	Modal Wave Period (sec)		% Prob of Sea State	Modal Wave Period (sec)		% Prob of Sea State	Modal Wave Period (sec)	
	Range	Mean	Range	Mean		Range **	Most Prob***		Range **	Most Prob***		Range**	Most Prob***
0-1	0-0.1	0.05	0-6	3	0.70	-	-	1.30	-	-	1.00	-	-
2	0.1-0.5	0.3	7-10	8.5	6.80	3.3-12.8	7.5	6.40	5.1-14.9	6.3	6.60	4.2-13.8	6.9
3	0.5-1.25	0.88	11-16	13.5	23.70	5.0-14.8	7.5	15.50	5.3-16.1	7.5	19.60	5.1-15.4	7.5
4	1.25-2.5	1.88	17-21	19	27.80	6.1-15.2	8.8	31.60	6.1-17.2	8.8	29.70	6.1-16.2	8.8
5	2.5-4	3.25	22-27	24.5	20.64	8.3-15.5	9.7	20.94	7.7-17.8	9.7	20.79	7.2-16.6	9.7
6	4-6	5	28-47	37.5	13.15	9.8-16.2	12.4	15.03	10.0-18.7	12.4	14.09	9.9-17.4	12.4
7	6-9	7.5	48-55	51.5	6.05	11.8-18.5	15.0	7.00	11.7-19.8	15.0	6.82	11.7-19.2	15.0
8	9-14	11.5	56-63	59.5	1.11	14.2-18.5	16.4	1.56	14.5-21.5	16.4	1.34	14.4-20.2	16.4
>8	>14	>14	>63	>63	0.05	18.0-23.7	20.0	0.07	16.4-22.5	20.0	0.06	17.2-23.1	20.0

* Ambient wind sustained at 19.5 m above surface to generate fully-developed seas.
To convert to another altitude, H_2, apply $V_2 = V_1 (H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

Figure 5.4.4.1-1 Annual Sea State Occurrences in the Northern Hemisphere

In many wingship design concepts the wing and hull are in contact with the water while drifting and provide a large waterplane area which may induce large translational and angular motions due to wave action. Also large pitch and heave motions may result in wetting of the PAR intakes.

The wave action will also produce wing bending loads. The magnitude of these loads also depends on the craft geometry. Prof. Logvinovich of TsAGI told us (Trip Report-Appendix G) that the sea-sitting loads were not critical and that landing loads were most critical. Although existing analytical ship motion computer programs may be ultimately adopted for calculating the sea sitting behavior of ekranoplans, model tests in towing tanks remain as the most reliable method for quantifying this area of performance.

To mitigate these potential problems, designers should consider geometry changes, slow speed maneuvering, and dedicated craft features (such as dampers or stabilizers).

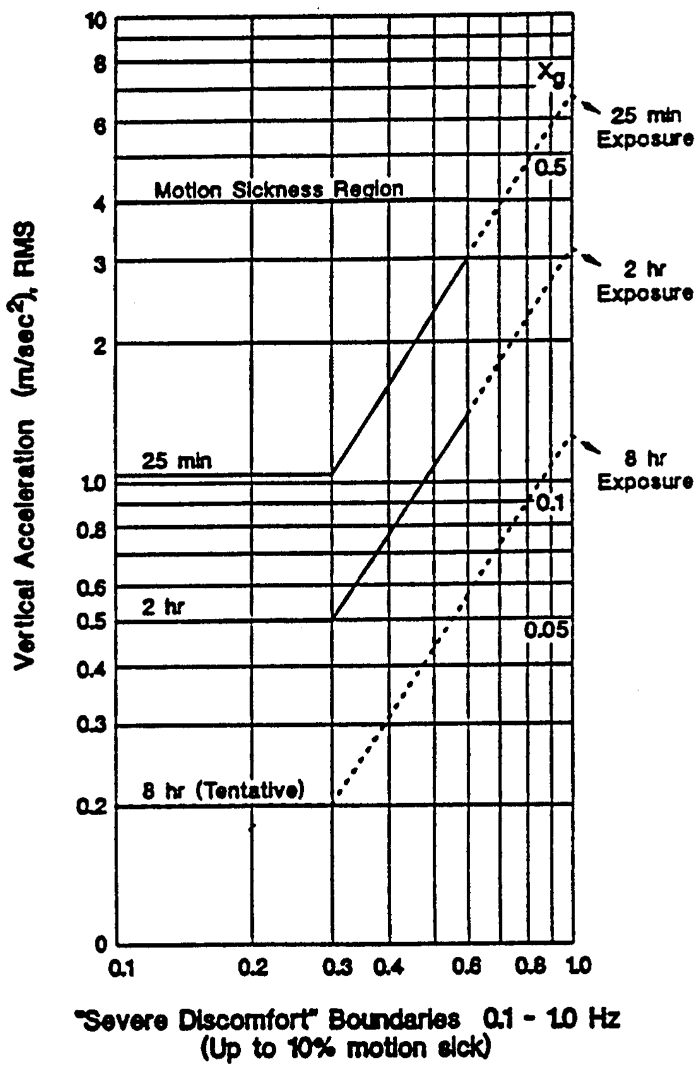

Figure 5.4.4.2-1. Human Tolerance - Motion Sickness

5.4.4.3 TAKEOFF IN WAVES

Ekranoplans usually take off with PAR activated in order to provide some additional lifting force to reduce the takeoff speed. As shown in Section 5.4.3, however, at the present time, takeoff speeds continue to be relatively high so that the vehicle is in contact with waves over a wide speed range.

At low speeds, where buoyant forces are still appreciable, pitch and heave motions are expected to be maximum. For sea states, where $H_{1/3}$ = .40 beam, green water may wash over the bow, windshield, wings, flaps and possibly flood the PAR intakes. The hull, wings and flaps are in contact with solid water and end plates are submerged. The hydrodynamic resistance is thus increased i.e. for $H_{1/3}$ = .40 beam the rough water drag may be 15% greater than the calm water drag.

These detrimental effects can be reduced if the vertical component of the deflected PAR nozzle is sufficient to increase the vehicle trim.

As speed is increased, hull hydrodynamic forces dominate while aerodynamic control is still small. Large spray sheets are developed as the hull slams into oncoming waves. The large kinetic energy of the spray can damage wing flaps if they are extended and not designed with load alleviating devices. In the Russian LUN, the wing flaps are only partially deployed in this speed regime to avoid contact with spray.

At speeds somewhat below takeoff, the hull continuously strikes the oncoming wave train. It develops impact loads which may be significant since hydroskis or other landing load alleviating devices may not be used during takeoff. The wing end plates are constantly penetrating the oncoming waves and must be designed to withstand large side forces if the vehicle is yawed.

In discussions with Prof. Logvinovich, we learned that hydrodynamic problems during takeoff in waves continue to be important and are one of the more important subjects for further study.

5.4.4.4 Landing Considerations

A "perfect" landing is one in which, after flare-out, the resultant velocity of the vehicle is nearly tangent to the free-water surface. In this instance, the craft settles into the water with minimal impact loads. Unfortunately, realistic flight path angles at water contact are not zero and the vehicle is at some positive trim angle relative to the water surface. Theoretical studies of the hydrodynamic impact process have established the relationship between the impact acceleration, flight speed V_O, flight path angle γ_O, hull trim angle τ_O, mass of the vehicle, and shape of the bottom. References 5.4.4.4-1 and 5.4.4.4-2 are typical of the many analytical studies of the impact process.

Figure 5.4.4.4-1 shows the vehicle landing on the flank of a regular wave. In this instance, the hull trim angle is measured with respect to the wave contour and the vertical velocity component is taken normal to the wave surface at the point of contact. There are few analytical or experimental data on wingship impact loads in a seaway and the Russians did not share their methodologies with the U.S. WTET.

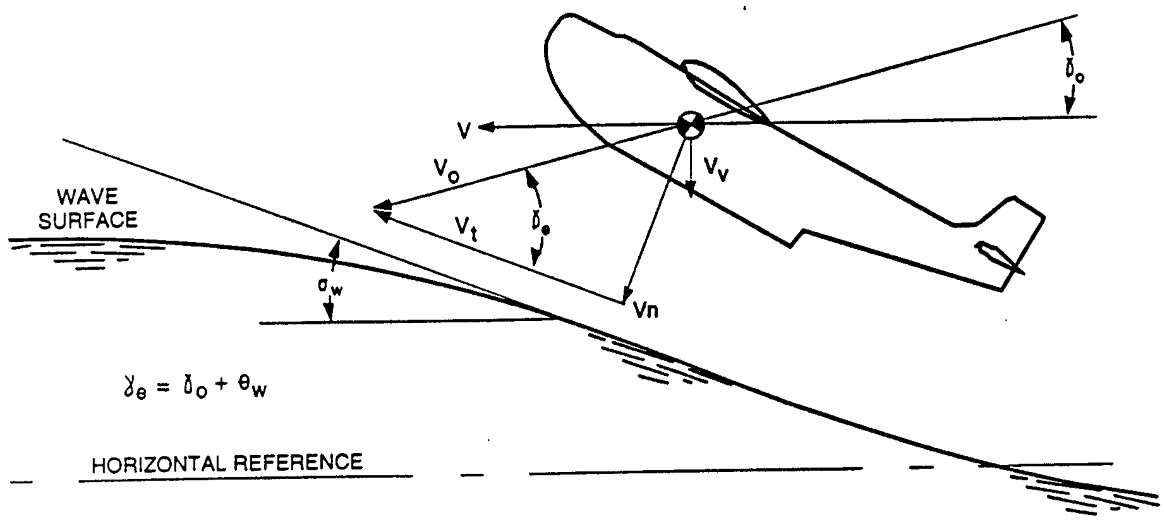

Figure 5.4.4.4.-1
Impact on the Flank of a Wave

To provide some guidance in the study, it is useful to refer to the extensive U.S. experience with landing of water-based aircraft. Water-based aircraft usually "bounce" off the initial wave and impact subsequent waves at steeper glide path angles and at different trim angles than the initial contact conditions. In fact, it has been found that the maximum impact loads in irregular head seas are developed in the subsequent run-out when there is little control of the aircraft-wave contact conditions. Empirical methods for estimating the impact loads for water-based aircraft landing in irregular seas have been developed based upon numerous model test results.

Smooth water landings, the impact acceleration is:

$$\eta = 0.00825\gamma_0 \, bV^2 \, \Delta_0^{-2/3} \left(1 - \frac{\beta}{90}\right)$$

Landing in irregular seas:

$$\eta = \left(\gamma_o + \theta_w\right)(.00825)\frac{bV^2}{\Delta_o^{2/3}}\left(1 - \frac{\beta}{90}\right)$$

where:

η = center of gravity impact acceleration, g's

γ_0 = flight path angle, degrees

Θ_w = critical wave slope = $\tan^{-1}\left[\frac{H_{1/3}\pi}{2LWL}\right]$, deg

$H_{1/3}$ = significant wave height, ft

LWL = load water line length, ft

V = landing speed, ft/sec

Δ_o = gross weight, lbs.

b = beam of craft or hydroski, ft

β = deadrise angle, deg.

It is to be noted that, in this empirical equation, the impact acceleration increases linearly with beam. Thus, since a hydroski has a smaller beam than the hull it is expected to reduce impact accelerations. This validates the use of hydroskis on Russian ekranoplans. As an example, the estimated impact load on the ski of the LUN landing in sea state 4 is:

$H_{1/3}$ = 6 ft

γ_0 = 5 deg (assumed)

LWL = 170 ft. (assumed)

b (ski) = 5 ft (assumed)

V = 285 ft/sec

Δ_o = 784,000 lbs

β = 5 deg (assumed)

Θ_w = 3.2 deg.

Therefore

$$\eta = 3.2g$$

During our discussions with Mr. Naryshkin of CHDB, he indicated that the Russians had their own empirical relations for estimating impact accelerations which were similar to the U.S. equation - but he did not share their method with us.

Dr. Logvinovich volunteered that the Russians design their craft for a 4g acceleration at the center of gravity and then estimate the maximum operational wave height using the following formula.

$$H_{3\%} = \frac{37.5g\nabla^{2/3}}{V^2}$$

where:

$H_{3\%}$ = average of 3% highest waves, m

∇ = displaced volume, m^3

V = landing speed, m/sec

g = acceleration of gravity, m/sec^2.

When the LUN parameters are substituted into the Russian equation:

$H_{3\%}$ = 8 ft.

or

$H_{1/3}$ = .65 $H_{3\%}$ = 5.2 ft.

This result is in reasonable agreement with the results from the U.S. empirical equation for water-based aircraft. Dr. Sokolov stated that the LUN has experienced 2.3 to 3.5g when landing in waves. This is also close to the U.S. prediction.

This agreement may be fortuitous. Both the Russians and the WTET agree that the landing process develops critical structural design loads.

5.4.4.5 Cruise Over Waves

Since the cruise speed may be 50% greater than the takeoff speed it is essential that the craft fly over the wave crests in order to avoid high speed impact with the wave. Obviously, this increase in wing clearance reduces the beneficial effect of ground effect and decreases the lift-drag ratio compared to flight over calm water where wing clearance can be reduced to as little as 10% of the wing chord.

There was no consensus as to the preferred elevation of the ekranoplan relative to waves when in the cruise condition. The following are several suggestions:

<u>According to Dr. Sokolov</u>

$$h = \frac{H_{3\%}}{2} + 0.10\,c$$

where

h = height of wing tip end plates above the level water
c = wing chord
$H_{3\%}$ = average of 3% highest waves

Relating this to sea state and our assumed wing chord of 40 ft:

Sea State	$H_{3\%}$	$H_{3\%}/2c$	h/c
3	4.3 ft	0.06	0.16
4	9.2 ft	0.12	0.22
5	16.0 ft	0.20	0.30

<u>According to Beriev Design Bureau</u>

$$H \geq 15'$$

Therefore for $c = 40$ ft, $h/c = 0.38$

According to the Wingship Compendium

$$h = \frac{H_{0.5}}{2} + 1.6 + 0.2H_{0.5}\text{ , ft}$$

In summary, the Beriev criteria will result in a substantial reduction in lift-drag ratio when operating in a sea environment. Dr. Sokolov's criteria lies between the Beriev and the Compendium criteria. This subject of wave clearance should be pursued with some vigor because of its significant effect upon cruise performance and structural design.

We were also told by Sokolov that ekranoplan pilots quickly increase the flying height upon first contact with the wave crests. As a result, it was reported that a maximum impact acceleration of approximately 0.2g has been recorded during cruise flight over waves.

5.4.4.6 Impact With Rogue Waves

Possible impact with unexpected large waves while in the high speed cruise condition is of concern to the ekranoplan designers. It was reported to WTET that a Russian wingship (unidentified) once struck a large wave at cruise speed and experienced an 8-10 g impact. This resulted in failures of engine bearings and support structure. All engines had to be replaced. Designing basic structure and mission payloads to tolerate impact of this magnitude is probably impractical.

Both Russian and American engineers believe that suitable wave sensing instruments can be installed in the vehicle to provide sufficient advance warning to avoid such impact with these unusually large waves. More study of this potential problem is strongly recommended.

5.4.4.7 Design Loads

Assuming that impact with the rogue wave can be avoided, the Russians believe that the landing impact loads are the critical structural design loads. While there is some guidance for selecting an impact acceleration (Section 5.4.4.3), it is recommended that model tests be conducted in a towing tank with the capability of generating specified wave spectra. Such tests will provide credible data for selecting structural design loads.

Of interest to the U.S. designers is the fact that the Russians apply a factor of safety of 1.8 to the hydrodynamic impact loads. Using the 2.3 to 3.5 g impact accelerations for the LUN, the design

accelerations would be between 4.1 and 6.3 g's. It is unclear whether the Russians design to yield or ultimate.

5.4.4.8 Hull Pressures

The bottom pressure magnitudes and distribution on the ekranoplan are expected to be similar to those experienced by a water-based aircraft when landing. There is a substantial analytical and experimental data base dealing with bottom pressures on water-based aircraft. Some of the earliest works were by von Karman (Ref. 5.4.4.8-1) and Wagner (Ref. 5.4.4.8-2). The NACA had a special towing tank facility at Langley, the Impact Basin, which was dedicated to studying the loads and bottom pressures during landings of water-based aircraft.

Some of the most significant results of these studies showed that a typical bottom pressure distribution during planing and impact is as shown in Figure 5.4.4.8-1. The conspicuous part of this figure is the sharp peak of pressure at the edge of the wetted area, with substantially lower pressures towards the keel. These pressure distributions in addition to the impact force itself are essential for proper design of the hull.

As the wetted length of the hull changes with speed, load, and penetration of the hull, the region of peak pressure, always located at the leading edge of the wetted area, traverses the hull bottom area so that almost any part of it is subjected to high local pressures at some time. The bottom plating and stringers supporting a very small bottom area should be designed to support the peak pressures. The supporting structure will be loaded by the average pressure over a certain larger area and can be designed for a lower pressure.

There are several methods for estimating the peak pressure and distribution as a function of deadrise, trim, and forward speed. The following equation is derived from the "expanding plate" analogy to a planing wedge developed by H. Wagner:

$$p_{max} = \frac{\rho v_0^2}{2\lambda^2}\left(1 + 2\lambda^2\right)$$

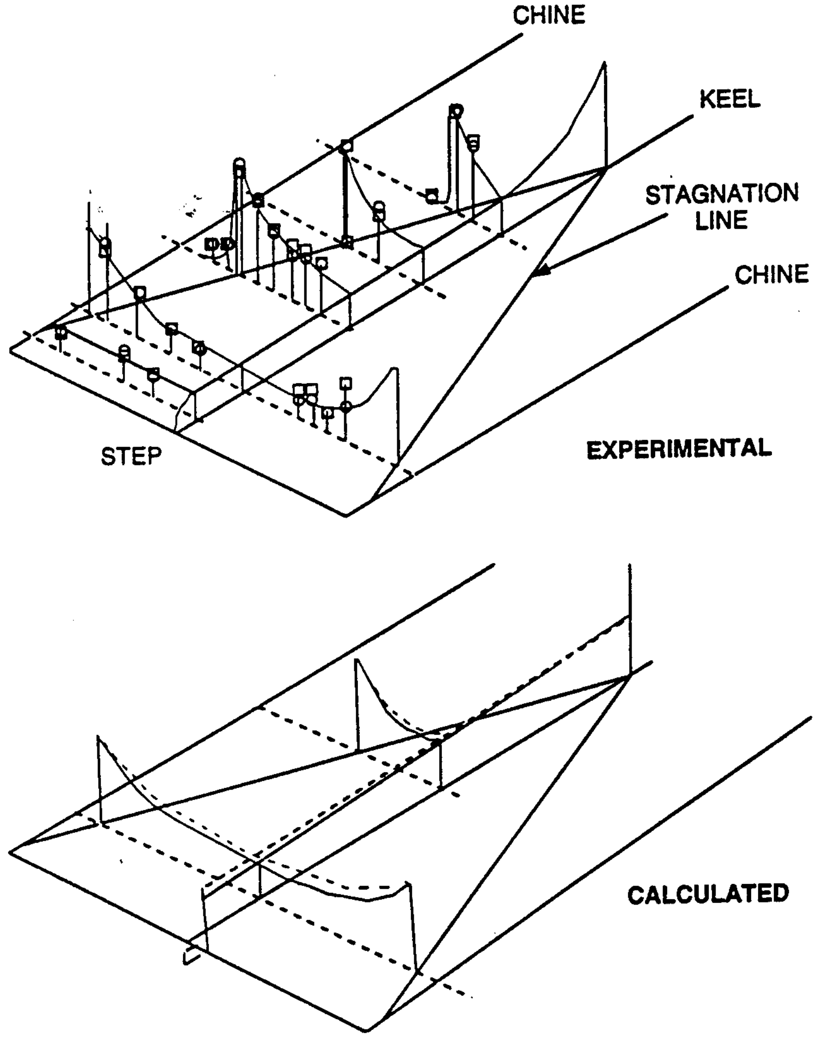

Figure 5.4.4.8-1 Typical Pressure Distribution on Seaplane Hull

where $v_O = V \sin \tau$, ft/sec

V = forward speed, ft/sec

τ = trim angle, deg.

$$\lambda = \frac{2 \tan \beta}{\pi}$$

β = deadrise angle, deg

Unfortunately, this equation is not applicable to the case where ß = 0°. However, for the flat bottom hull or hydroski, the peak pressure is simply the full stagnation pressure. Thus:

$$p_{max} = \frac{1}{2}\rho V^2 \quad \text{for } \beta = 0°$$

This pressure is independent of trim angle.

The above equations are for the case of steady state planing. Smiley (Ref. 5.4.4.8-1) showed that the pressure distributions are essentially the same for steady state planing and for the case of impact where the hull has both horizontal velocity, V, and a vertical velocity v. He showed that:

$$p_{max} = \frac{1}{2}\rho f^2$$

where:

$$f = V + \frac{v}{\tan \tau} \quad = \text{(equivalent planing velocity)}$$

v = vertical velocity of hull

To illustrate, the above-the-peak pressure estimated to be applied on the LUN hydroski is now calculated assuming the deadrise to be zero degrees:

For the planing condition:

v = 200 ft/sec (assumed)

$$p_{max} = \frac{\rho}{2} \; \frac{(200)^2}{144} = 270 \text{ psi}$$

For the impact condition:

v = 5 ft/sec (assumed)

τ = 15 deg

$$p_{max} = \frac{\rho}{2} \; \frac{(219)^2}{144} = 330 \text{ psi}$$

The WTET was informed by the CHDB, that the maximum pressure measured on the LUN hydroski was approximately 20 atmospheres or 294 psi. This appears to verify the above estimate which was based on a realistic planing and sink speed.

These methods may also apply to the "wave clipping" phenomena at cruise speed. Ron Jones, a designer of 200-knot unlimited class racing boats, reports that honeycomb materials rated at 1100 psi fail and those rated at 1600 psi survive.

5.4.5 Propulsion

Five major topics were considered in establishing propulsion capability needs for future wingships. Discussion of each topic addresses both U.S. knowledge and Russian experience and project technology and/or design needs for a successful U.S. effort in the future. The reader is directed to Appendix K for expanded information and more details. Most of the focus is on jet engines and derivative concepts, but nuclear propulsion is addressed in Subsection 5.

1. **Water/air separation** - Substantial amounts of sea water can enter the engines at takeoff and landing as "green water" plus small liquid particles of water are ingested with the air. Both are undesirable, but the small particles are likely the worst since this causes salt deposits in both compressors and turbines which rob needed operational margins in core EGT and stability. The Russians plan on 50-60 deg C. EGT gain before washing off salt deposits (see Section 6.2.4 on these requirements). Initially they used very complex doors and venetian blind type inlet systems, despite the large inlet pressure losses one might anticipate from such devices. Their LUN under construction was to use a much simpler system. The hardware seen used an inlet bullet nose shaped like an onion or Greek Orthodox church spire, point end into the wind, to deflect large drops and spray larger than 3-5 microns in diameter. Separation occurs when the high inertia drops cannot follow streamlines. GE has used a similar system on the CFM56 installations to keep water out of the core to avoid apparent flameouts during idle descents in very heavy rainfall. The Russians assume extensive amounts of small water particles will not be defeated by a separator and will indeed enter the core (See Section 6.2.4). **Our inlet designs should assess the same method.**

2. **Engine cycle selection and design** - To date, the Russians have not used unmixed-flow turbofans, but only because PAR requires some method of deflecting both core and fan streams.

Unmixed-flow engines have two nozzles - one for the core and one for the fan further upstream. All mixed-flow turbofan engines used by them for PAR, like the NK-87, have used an external clam shell after the nozzle that deflects the exhaust flow under-the-wing. A ship big enough to use the only engines in development today in the 100K Lb thrust class (like PWA 4084, GE 90 or RR Trent), will have to deal with the fact that these engines are unmixed-flow turbofans. The Russian thrust deflection scheme for them would be to rotate the canard they are mounted on. An alternative considered by the U.S. to reduce airframe complexity (at the expense of gaining it in the engine) was to translate the fan nozzle aft for TO and then pull it forward upon wingborne flight to avoid fan/core stall. The Russians thought this too complex and heavy, and **it is recommended that for future design work in the U.S. we rotate the canard, with the engine thrust line close to the spar centroid.**

A major cycle issue is that takeoff thrust/weight ratio is so high as to oversize the engines at cruise. This in turn forces them to operate inefficiently where SFC is up to 15-25% higher than at normal aircraft cruise values. At cruise, the Russians shut down several inboard engines to alleviate this problem somewhat, despite penalties in windmill drag. To reduce these problems, both we and the Russians have looked at thrust augmentation to boost TO power as a means of using fewer engines for TO thrust. They claim water injection at the compressor discharge would provide 12% augmentation on the Trent. With a "wet" wing, they would limit the fan-out temp (for a fan duct burner) to the JP limit for hot surface ignition - about 220 deg C.(430 deg F.), which buys an augmentation of 22-23%. If we could allow a higher fan-out temperature, by insulating the wet tanks or filling the ullage above the fuel with nitrogen, to about 800 deg F., the augmentation for the entire engine would be about 38%. Thus, a dry PWA 4084 at 83,074 pounds thrust would produce 115,000 lbs thrust "wet" via a duct heater at 800 deg F. fan-out temperature. This might help reduce a 10 engined wingship to 6 engines, with better cost, weight, drag and SFC. The safe wet wing will be a difficult item as will be the low pressure, low temperature duct heater augmentor. Both could use study with substantial payoffs expected for success. **It is strongly recommended that the U.S. designs study, employ and then develop both a safe wet wing and a fan duct burner for at least 38% thrust augmentation. Risk is substantial. For all the low power operation, we might also evaluate the benefits from increased airfoil solidity as a means of getting better SFC.** Recognize however, that this would represent a major change to any existing engine and would likely apply only to an ekranoplan engine as yet unbuilt.

When asked what would be high on his priority list for an engine designed just for ekranoplans, the head of Russian Ekranoplan engine development said engines for these applications needed more than just coatings for corrosion protection. Where the cruise engines needed to have the best aircraft engine attributes to be had, any **"lift" or PAR only engines needed moderate characteristics - low pressure ratio to avoid salt deposits at high compression temperatures, lots of low cycle fatigue life, high reliability, and 50-60 deg C. EGT reserve for salt ingestion.** The "TO only" engines use optical boroscopes and external TV systems for internal viewing. He also indicated that a reduction in max TIT at TO of 100-150 deg F as on shipboard marinized aircraft engines was done - with loss in thrust.

3. **Engine reliability and vehicle availability** - See Section 6.2.4 for discussion of this aspect of engine operations.

4. **Environmental issues (noise and sea salt combustion products)** -The U.S. DoD now has environmental regulations (Acquisition Directive and Instructions 5000.1 and 5000.2 of 1989 and 1991) forcing it to determine, disclose, investigate, mitigate and incorporate considerations to not make hazardous effluents during all phases of a weapon system's life cycle, including development and training. The noise from 6-10 large conventional turbofan engines at TO (about 112 to 126 pNdB vs 120 for the threshold of pain) would likely demand they be towed or auxiliary power driven to and from the sea for landings and takeoffs. The PWA 4084 design is a geared fan, which may be inherently quieter than conventional CF6s or JT9Ds. Assuming however that noise would be a problem, a key factor is that local i.e. state, county, and municipality laws govern here. The Russians were keen to learn more about commercial developments in the U.S. for noise suppression tailpipe ejector nozzles to meet FAA aircraft noise regulations. A good source on this is Dr. Yulu Krothapali at Florida State University, Tallahassee Fl who developed the ones on B727s today. For wingships, we need to look hard at what is known today about reducing engine noise and making an assessment of what it will cost in dollars, weight and performance to incorporate this into engines for wingships. **With double the engines of a 7X7, wingships will be at least 3 to 5 dB noisier than the FAA regulations permit.**

The following discusses the emissions of combusted air containing sea salts. Each 1000 grams of water in the "average" ocean contains 42 grams of chemicals besides H_20, about half of which is NaCl (see ASTMD-665 spec). The other major constituents are $MgCl_2$-$6H_20$, Na_2SO_4, $CaCl_2$ and KCl. These five make up all but 0.4 gms of these materials. **A definition is needed of the combustion products of these materials during starting and operations and their**

health effects upon human beings. Under the right conditions of combustion of a hydrocarbon, one of these materials (NaCl) can produce $C_{12}H_4O_2Cl_4$ - which is dioxin, a known carcinogen in humans. It is not known if engines (particularly during startup with salt water in their combustors) can produce dioxin. It is however a fact that in the 1970's, 4 men from a USN test facility who were the engineers and crew on a very severe salt water ingestion test of a turbine engine about 7-10 years prior, all died of various forms of organ and brain cancers. This was the only test known at that facility where all four men worked together. Any correlation between these tests and their deaths is not known, nor is it likely to ever be known. However, it does seem that basic combustion studies and lab tests would be worthwhile to identify what the health effects are from jet fuel combustion in the presence of the various chemicals in sea water, not just NaCl. The operators and passengers of wingships and nearby residents of basing areas would be at risk if a problem is detected.

5. Nuclear propulsion - In the late 1950s, the U.S. was considering an open cycle gas turbine for bombers that could be on station for extended periods. In concept, the cycle simply passes compressor discharge air through a nuclear fired heat exchanger in lieu of a combustor, and then back in at the turbine entry. The concept was rejected when it became evident that the weight of shielding would drive the vehicle gross weight into the 750,000 lb class. Since wingships start in that weight class and work upwards in size, nuclear propulsion may be applicable to this vehicle. It would certainly tend to mitigate problems and issues regarding range as an inverse function of wave height. The Russians stated that during the same time period, they considered their NK12 turboprop (same one used on the Ekranoplans and also on the 4 engined "Bear") for nuclear applications and actually modified and ran one with a nuclear pile. They said they terminated the project owing to the radiation hazard created by irradiated particles in the air as it passed through the system and back into the atmosphere, which is a predictable characteristic for an open cycle gas turbine.

It was suggested to their propulsion expert (Gregory Perevozkin) that they might wish to reconsider nuclear, but now using **a helium filled closed cycle,** such as we have considered for space power and the Germans have built in a 25 MW (30,000 SHP) ground based electrical power generating station. They expressed great interest in this, possibly because it would emit no radiation from the trapped working fluid.

To keep takeoff thrust from driving this scheme to very large piles and weights, it should consider using an externally fired topping burner using liquid fuel to boost TIT by 200-300 deg F. for TO only. This would allow the minimal cruise thrust requirements to drive and size the nuclear pile

and heater exchanger. **In further phases of U.S. design and cycle selection, this cycle is very worthwhile for examination and should be given a high priority for wingships.** Cycle decks to assess their performance characteristics using a topping burner are available.

5.4.6 Air Injection

Takeoff performance is fundamentally a product of (a) vehicle lift generation capability which determines the speed at which it can depart the surface, and (b) thrust available which determine the takeoff distance required to achieve lift-off speed. Fundamentally significant differences exist between PAR-WIG and seaplane vehicles for takeoff (and landing) operations as discussed below.

Lift, thrust and configuration variables for PAR-WIG takeoff are illustrated in Figure 5.4.6-1. The weight of the vehicle is initially supported by hydrodynamic floatation with flaps retracted and engines set at a reduced power (approximately 20%) to prevent excessive spray. Engine nozzle position is set at zero deflection. At a nominal speed (tens of km\hr) the engine throttles are advanced to full thrust and the flaps are progressively extended as speed is increased. PAR lift is generated which off-loads the hydrodynamic lift required. Because angle of attack variations for in-ground-affect operations is limited, the vehicle is heavily dependent upon PAR lift until a speed is attained for which the vehicle weight can be supported by aerodynamic lift alone. This occurs near cruise speed where the flaps can again be progressively retracted and the engine nozzles returned to the undeflected position.

PAR operations generally yield lift augmentation but at the expense of net thrust recovery available for acceleration. The data gathered by Gallington (Ref. 5.4.6-1) support this trade-off trend since the PAR operations yields positive cavity pressures but also results in reduced net thrust recovery.

For a seaplane, the vehicle weight is also initially supported by buoyancy. However, takeoff flaps are deployed (except in special cases to avoid spray damage) and full thrust is applied at takeoff initiation. The vehicle accelerates to takeoff speed, rotates to an appropriate angle of attack to depart the water surface supported entirely by aerodynamic lift using full thrust. This procedure is also illustrated in Figure 5.4.6-1.

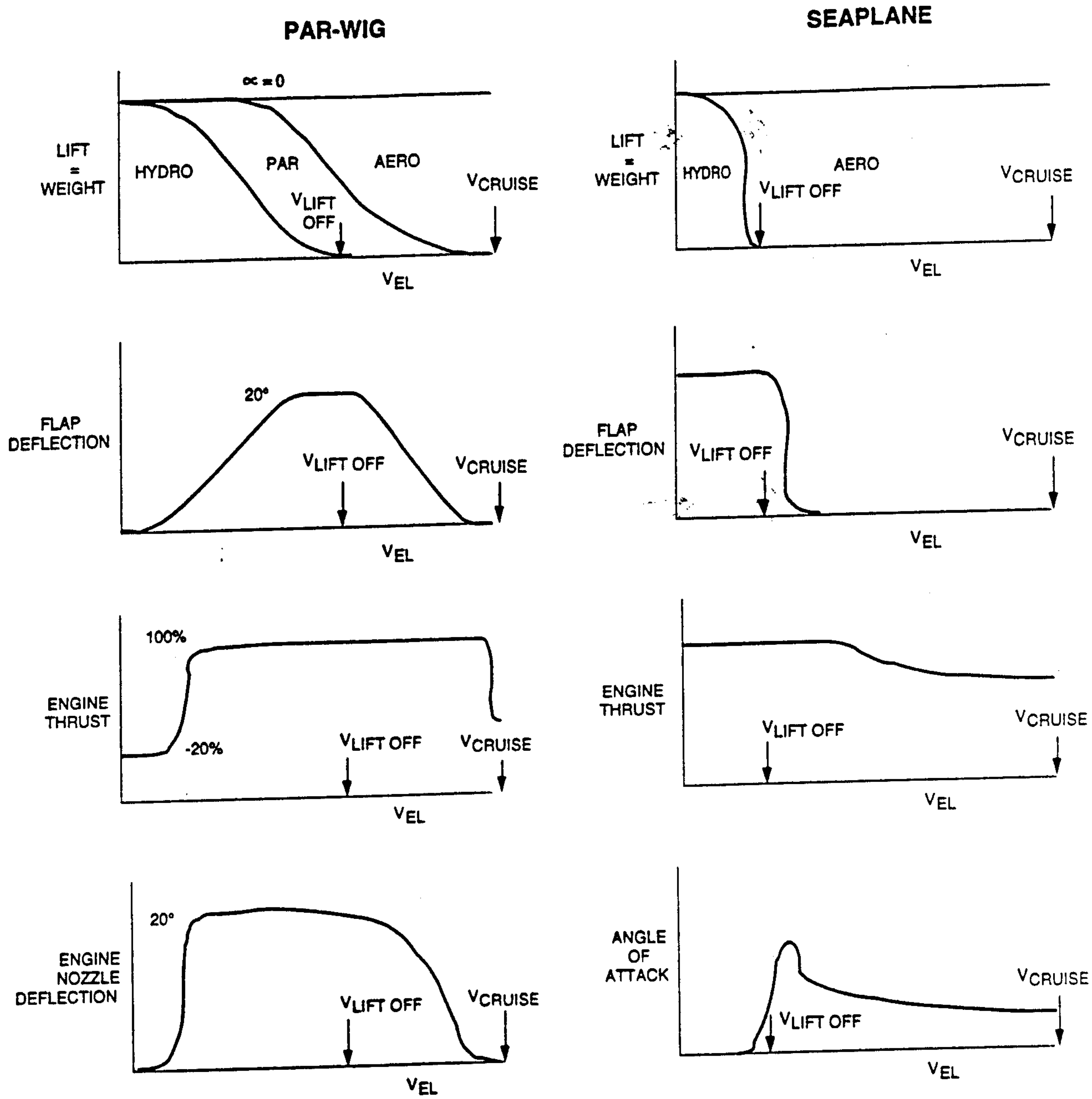

Figure 5.4.6-1 Takeoff/Acceleration Operations

Two conclusions can be drawn from these comparative procedures;

- The dependence upon PAR lift up to speed approaching cruise conditions causes water contact at high speeds.
- Thrust available for acceleration is also reduced in the PAR mode resulting in long takeoff runs (3 to 5 km).

The Russians may not have appreciated, early in their program, the low speed limitations of PAR operations due to spray and angle of attack limitations which have apparently resulted in extended high speed takeoff runs. Foreign viewers believed, until recently, that the Russian vehicles were able to lift-off and clear the water surface at very low speeds using the PAR mechanism.

5.4.7 Structures, Materials And Weights

Structures: The design of structures for large wingships is very complex because the vehicles have to operate in the boundary conditions of air and the ocean's surface. This environment is further complicated by the ocean's wave action. In addition, the overall structural configuration of a wingship is influenced by the type of payload it carries, by the mission requirements such as speed, range, flight altitudes, and by the takeoff and landing sea conditions and the takeoff and landing speeds.

The added capability for a very large WIG to land on hard ground surfaces is not feasible due to the high structural weight penalties from the additional landing loads and the weight of the landing gears. The added capability for a wingship to fly at higher altitudes requires vehicle pressurization which also would impose a structural weight penalty. Up to this point, the Russian wingships do not use pressurization. Studies on regular transport aircraft have shown that takeoff/landing loads and pressurization loads are most important for short-range aircraft, and the gust and maneuvering loads become secondary. The payload of short-range aircraft has also a higher impact on the structural design. For long-range aircraft, on the other hand, gust loads, pressurization loads and flight duration at high altitudes are of primary concern and takeoff/landing loads become secondary.

The design of a wingship structure requires the merger of two technologies: aircraft design and high-speed-ship design. Both technologies have one criterion in common: that is to design a very

weight efficient structure with high resilience and good producibility. Only a limited amount of structural area research has been done outside Russia. Outside Russia, most published data on structures is based on aircraft design approaches, existing aircraft data and existing aircraft weights.

The present state-of-the-art of large wingship structures is found in the Russian design of the ORLYONOK class and the LUN class, which are both in operation. The Russian wingship structure technology evolved at first from the technology of hydrofoil boat design. But, Russian designers have integrated aircraft structure technology wherever it was necessary. Since the 1960s, Russian scientists and engineers have worked on the various complicated problems of wingship design and have developed this technology to its present successful stage. Wingships of over 500 tons gross takeoff weight (GTOW) have been built and flown, as mentioned earlier. According to the Russian designers of the ORLYONOK and LUN class vehicles of the Central Hydrofoil Design Bureau (CHDB) in Nizhny-Novgorod, wingships up to 800 tons GTOW could be designed and built today with a high confidence level. The basic material for the structure of such Russian wingships would still be aluminum alloy. According to Russian studies, titanium would be feasible for sizes above 1,000 tons GTOW.

Present Russian technology uses a lower strength (about 67% of common aircraft-grade aluminum) but weldable aluminum/magnesium alloy with high corrosion resistance against salt water. This alloy is used for the majority of the large wingship structures. For the remaining part of the structure, mostly internal, a heat-treated aluminum alloy is used which is comparable to our high-strength aluminum alloys used in the aircraft industry.

The high loads of the takeoff and landing conditions require substantial scantlings. This makes it feasible to use welded joining methods due to the plate thicknesses required for the fuselage and wing skin plating, thus maintaining the required buckling strength. This approach reduces the weight penalties for lower-strength aluminum alloys. About 60% of the ORLYONOK wingship structure is welded and about 90% of the LUN wingship structure is welded. Another reason according to the Russians for using welded joining methods was the difficulty of maintaining watertightness of riveted or bolted connections in the waterborne conditions. In addition, fabrication costs can be reduced substantially by using welded joining methods.
Based on observations made in Russia on a LUN class wingship under construction, the quality of wingship construction and joining methods is very good under the conditions of their average fabrication facilities. Normal quality inspection methods are used for the welds, such as X-ray and ultrasonic testing.

In summary, the present technology of the design and fabrication of larger wingship structures does not present major problems or uncertainties as long as the loads are predicted correctly. Features such as the configurations of the fuselage, wings, and hydroskis, require technology transfer and development involving larger risks.

Materials: The material used by the Russians for the welded structures is the Russian aluminum alloy AMG 61 (34 kg/mm^2 ultimate tensile strength). The U.S. equivalent is the alloy series AL 5086 and 5456. This material applies to the basic fuselage, the wings, the endplates and the hydroski.

The Russian alloy K48-2PCH (44 kg/mm^2 ultimate tensile strength) is utilized for internal riveted structures such as decks, transverse bulkheads, and partitions. It is a high-strength alloy and is used for weight optimization in components less critical to the survival of the vehicle. Stainless steel is used by the Russians for the engine pylons which require high-strength and heat resistance.

Corrosion protection is accomplished by the Russians with the use of their AMG 61 aluminum alloy which has a high resistance against saltwater corrosion. In addition, the total exterior wingship surface is coated with anti-corrosion paint.

Few uncertainties exist in the areas of materials and corrosion protection, if equivalent materials are used on future U.S. wingships. As aluminum alloys are being substituted with other lighter and stronger materials, such as titanium and composites, additional research and development, including extensive testing, is required. The areas of buckling and fatigue strength become more critical as well by using stronger metals and composites, since scantlings become relatively thin with increasing vehicle sizes.

The complex, cost-intensive fabrication of the hull and wing structure that is subjected to buckling and to the hydrodynamic loading can be addressed by changing the structural concept and materials. Composite sandwich structure, as used on high performance racing boats and on light aircraft can be tailored to local loads, and can be manufactured at low cost. Using a combination of carbon fiber and glass fiber with thermoset or thermoplastic matrix can result in a structural weight savings of 15 to 25% as compared to aircraft aluminum and as much as 40% compared to the Russian welded materials.

Weights: The structural weight fraction of wingships is one of the most important parameters in the design process and one of the most difficult parameters to predict with any reasonable

accuracy. It takes almost a complete wingship design process to produce one point for a curve of structural weight fractions.

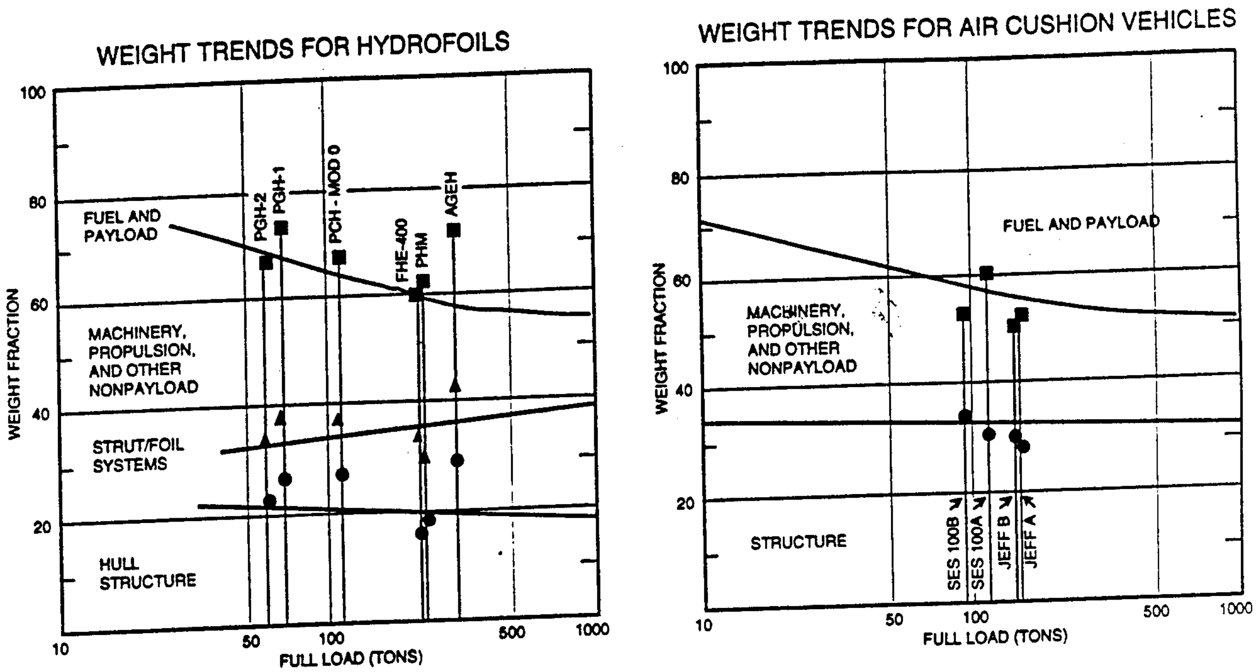

Figure 5.4.7-1
Weight Fractions for Hydrofoils and Aircushion Vehicles

Any weight information from the U.S. data base and from any parametric study, including the one performed for this report, may be optimistic since it is based on aircraft design practice. We have attempted to approximately correct this optimism by assigning factors to the aircraft weight equations based on weights of the Russian designs.

Probably the most realistic structural weight fractions for the ORLYONOK and LUN class wingships were provided to the WTET by the Russians (Appendix H-1). The ORLYONOK/LUN are not qualified for the open ocean environment, thus their weights may be non-conservative. On the other hand, it may be assumed that there is a certain amount of material in the Russian designs which is not utilized due to the high factors of safety applied for certain loading conditions. One of the problems for the wingship designer is the scaling effect in estimating weight fractions for wingships of much larger sizes than the existing ones. Figure 5.4.7-1 shows weight fractions for hydrofoil ships and air cushion vehicles using aluminum alloys. The data in both cases indicates a decrease of the structural weight fraction as vehicle size grows tenfold. High-speed-ship weights are probably a better indicator for ocean-capable wingships than aircraft weights.

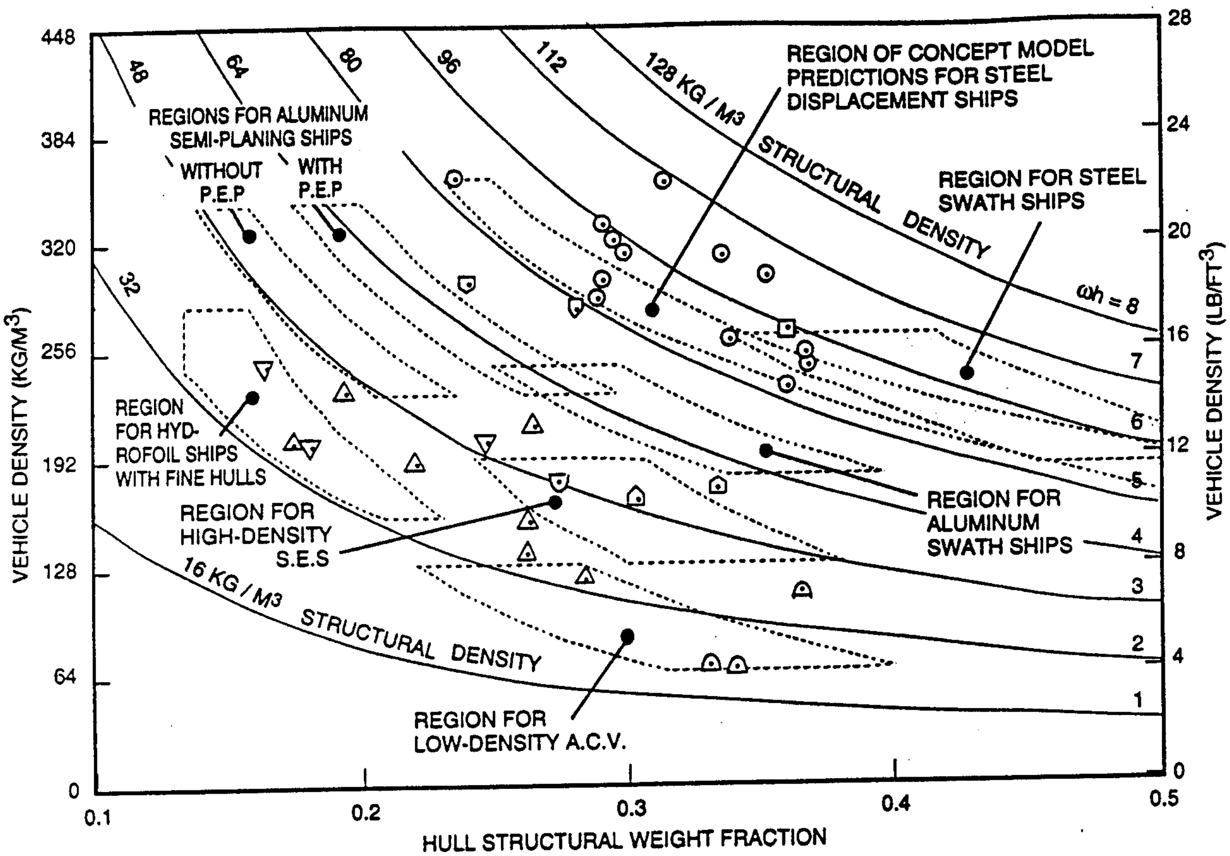

Figure 5.4.7-2
Vehicle Density vs Structural Weight Fraction

The structural weight fraction as a function of vehicle structure density (i.e. the structural weight divided by the vehicle volume) is also a good tool in the early design stages. The scantlings of the major structural components are, of course, a function of the loads applied to the wingship in the various loading conditions. At the same time, the majority of the structural weight depends on the volume that has to be enclosed by the structure of the wingship, which is a function of fuel, cargo, crew and machinery to be carried. The Figure 5.4.7-2 shows vehicle densities (i.e. the gross vehicle weight divided by its volume) versus structural weight fractions of various vehicle types such as hydrofoil ships, air cushion vehicles, surface effect ships and semi-planing ships. Wingship structures probably fall in the range of 30-50 Kg/M3 densities.

The large structural weight fractions of the ORLYONOK and LUN make them unsuitable for long range missions. Improvement may be accomplished by the application of a combination of carbon

fiber and other composites and titanium, by very accurate load prediction methods, and by applying unconventional structural skin/stiffening concepts as used by Scaled Composites Inc.

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6. System Evaluation

6.1 Long Range WIG Parametric Analysis

It is well recognized that wing-in-ground-effect vehicles should become increasingly more range-efficient with increasing size. The phenomenon results primarily from the increase in lift-to-drag ratio with decreasing flying height-to-wing-span ratio and from the requirement to over-fly a specified surface roughness, e.g., sea state condition. This anticipated increase in efficiency with size also results from a decrease in weight empty-to-gross weight ratio with increasing gross weight, permitting a larger useful load fraction (payload plus fuel). It is this rationale that drove the Russian program very quickly to large size vehicles. The question naturally arises relative to the performance payoff that might be available for even larger vehicle sizes.

In order to assess this potential, a parametric study was conducted that projects vehicle performance from the current Russian gross weight limit of approximately 400 tons to 5,000 tons gross weight. The level of analysis provides a first-order assessment thought to yield reliable trends and absolute performance levels consistent with the Russian experience. The reader should remember, however, that the study is anchored to a Russian design at the minimum parametric study weight and is extrapolated by over an order of magnitude in vehicle gross weight.

Primary assumptions. methodology and results of this study are summarized in this section. Appendix C presents, for reference purposes, more detailed information used in the generation of this study.

6.1.1 Study Approach

The study is based upon the highly developed WIG type of configuration. The specific configuration selected is the SPASATEL vehicle which is the latest large Russian vehicle under development and is assumed to represent the culmination of their WIG experience to date. The SPASATEL is the smallest size vehicle included in the parametrics and thus represents the study anchor point. This approach lends a degree of credibility to the study due to the use of an existing design.

The parametric approach allows the wing aspect ratio and wing loading to be optimized for maximum range as the vehicles are sized for various design payload/range capabilities. Key fuselage parameters such as length-to-beam ratio and height-to-beam ratio are held constant. Horizontal and vertical tail volume ratios are held to those of the SPASATEL.

It is recognized that the most efficient configuration geometry may optimize to a different configuration type for the larger vehicles. One of the Russian comments in response to a query concerning large WIG vehicles was that the configuration would more likely be a flying wing. The investigation of configurations other than of the SPASATEL type, however, is beyond the scope of the current study, requiring considerable conceptual development work for which a database is lacking. Therefore, study ground rule excluded more general configuration types. Many comparative aircraft parametric studies show that configuration type frequently does not influence range performance greatly. Operational considerations are usually major configuration drivers.

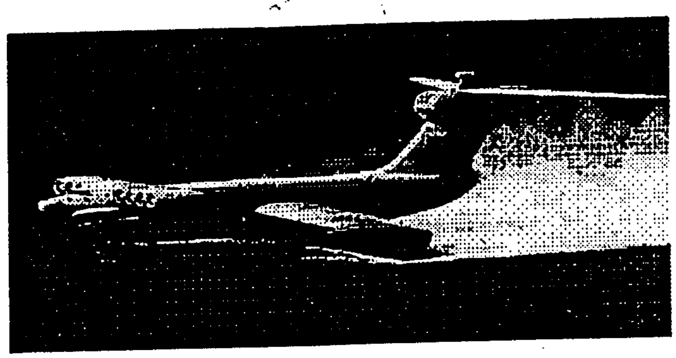

Figure 6.1-1 Russian Spasatel

A reference drawing of the Russian SPASATEL vehicle is included as Figure 6.1-1 dimensional and weight data are in Figure 5.2-1.

Wingship visionaries have imagined a blended wing-body concept (see Figure 2.2-1) and set some performance goals for such a concept. In cases where it is appropriate, the charts that follow will compare the performance goals of this blended wing-body concept with the parametric results.

Basic considerations used to generate the parametric study are summarized below with more detailed information included in Appendix C.

• Vehicle Weight

Weight was estimated using standard aircraft regression data corrected for WIG peculiarities using a component weight breakdown for the SPASATEL vehicle supplied by the Russians

(Ref. Appendix H-1). The correction factors automatically account for weight increases due to hydrodynamic loads, materials and methods of manufacture used in the SPASATEL. The design landing impact load is four gs. These weight estimates have a major impact on vehicle size and gross weight required to meet a specified payload and range capability. They are also the most uncertain of the fundamental aerodynamic and propulsion performance factors. A reduction of 20 percent in structural material weight is used compared to the SPASATEL weight to account for the use of advanced material, e.g., composites.

- Aerodynamics

Cruise - Zero lift-drag is calculated using standard drag estimation methods based on component wetted areas, geometries and associated Reynolds numbers. Induced drag is calculated using the equation from Wieselsberger (Ref. 5.4-1).

$$C_{D_i} = \frac{C_L^2 \left(1-\sigma\right)}{\pi \, AR \, \varepsilon} \quad \text{where } \sigma = e^{-2.48(2h/b)^{0.768}}$$

The comparison of induced drag estimation methods discussed in Section 5.4.1 shows that the selected method for the parametric study (Weiselsberger) is optimistic but is used to represent wing design tailored for minimum induced drag.

Takeoff - Takeoff distances and speeds were not calculated due to the difficulty (impossibility) of such calculations, as confirmed by Russian discussions. Vehicle thrust requirements, however, are determined by lift off and acceleration during the takeoff run. The details of this procedure are based on test data from DTNSRDC (1976) and are discussed in Appendix C.

Landing - Landing performance is not expected to set any performance parameters affecting vehicle sizing and is not estimated. Certain structural weights, however, are determined by landing (four g impact) loads according to Russian testimony. These weight penalties are "built-in" to the parametric weight estimates by "indexing" to the SPASATEL.

- Propulsion

The propulsion system used in the parametric study is based upon the Pratt & Whitney 4084 engine. The engines were scaled up 24 percent from their rated size and incorporated fan duct burning, raising the takeoff thrust available an additional 35 percent. The number of engines required is dependent upon takeoff acceleration requirements. This percentage scale up of engine dry thrust is consistent modern engine series development. The cycle and installation features of this engine are given in Section 5.4.5 including installation issues as applied to WIG applications.

- Performance Assumptions

The calculated vehicle performance is based on a few key ground rules and operating conditions.

Takeoff-	5 minutes fuel allowance with all engines operating at max power
Fuel Reserve-	5 percent fuel flow conservatism Range to alternate base of 350 nautical miles
Cruise Mode-	The vehicle can adjust to weight decrease due to fuel burn off during cruise in one of three ways:

1. Maintain constant C_L (constant L/D) and decrease speed as weight decreases, or
2. Maintain speed and cruise height in ground effect as weight decreases (decreasing L/D), or
3. Maintain speed and increase cruise height as weight decreases (decreasing L/D from ground effect).

These three methods are compared assuming a vehicle gross weight of 5000 tons and a payload fraction of .20.

CRUISE MODE	RANGE
1. Constant L/D and height, vary M -	6685 NM
2. Constant M and height, vary L/D -	5880 NM
3. Constant M, vary height and L/D -	4265 NM

The cruise method selected for the study was flight at constant C_L and cruise height (staying in ground effect) because of its better range efficiency (in accordance with ground rules).

The number of cruise engines required is significantly less than the number required for takeoff. This engine "mismatch" is fundamental to the PAR-WIG concept. Three operational options exist to account for the penalties of inoperative engines during cruise:

1. Shut down the unneeded engines and incur a windmill drag penalty, or

2. Maintain engines at a low power and suffer a fuel penalty, or

3. Shut down the unneeded engines and feather the fan blades.

The least penalty for carrying inoperative engines is to feather the fan blades. The drag penalty is estimated to be 35 percent of that of the windmilling option. It is assumed that the variable pitch fan would yield a 10 percent improvement in sea level engine performance but would incur a 10 percent increase in engine weight for gearing.

- Design Sea State

  A design sea state of 4 was selected for cruise performance calculations. This sea condition has a mean significant wave height (1/3 highest wave) of 1.88 meters (6.2 feet) and has a probability of occurrence in the northern hemisphere of 29.7 percent. Flying height for this condition is selected to clear the 1,000th highest wave which is approximately twice the significant wave height or approximately 12 feet. Higher sea states can easily be accommodated operationally by increasing flying height, albeit at a range penalty.

- Sizing Approach

  The sizing process used integrates the disciplines of configuration, mass fractions, aerodynamics, and propulsion and provides insight on how each impacts the total vehicle design. Vehicle payload/range performance provides the metric for determining the optimized vehicle. Parametric studies were developed for the design parameters of gross weight, aspect ratio, wing loading, and payload with range as the dependent variable.

The parametric study was performed in two distinct steps.

1. Size optimum range vehicles for a given gross weight and payload/gross weight ratio for varying wing loading and aspect ratio.

2. Select a vehicle from the parametric study with which to conduct sensitivity studies. The vehicle selected was a 5000 ton gross weight, .20 payload fraction vehicle. Results of these studies which are presented in Appendix C include these sensitivities:

   Wing Aspect Ratio
   Wing loading
   Wing thickness ratio
   Fuselage width
   Fuselage depth
   Weight empty fraction
   Payload fraction
   Structural weight fraction
   Takeoff altitude
   Cruise height
   Cruise altitude (S.L. and 5,000 feet)
   Engine scale factor
   Thrust augmentation factor
   Specific fuel consumption

6.1.2 Parametric Study Results

Pertinent results from the parametric study are presented in this section. Relevant geometric weight and operational performance parameters are first shown for the basic design parameters and assumptions as discussed in the previous section. Sensitivities to these basic assumptions are then presented and illustrate their impact on vehicle sizing. Sensitivity studies frequently provide an excellent indicator of areas of emphasis or technology improvements that can provide significant performance gains.

6.1.2.1 Basic Vehicle Sizing

The range capability of vehicles with design gross weight up to 5,000 tons is shown in Figure 6.1.2.1-1. Each point on the curves represents a uniquely optimized vehicle in terms of wing geometry, best cruise speed, etc. The gain in range diminishes as design gross weight increases. A design range of 10,000 nautical miles is attainable for very large WIG vehicles with relatively small payload capacity.

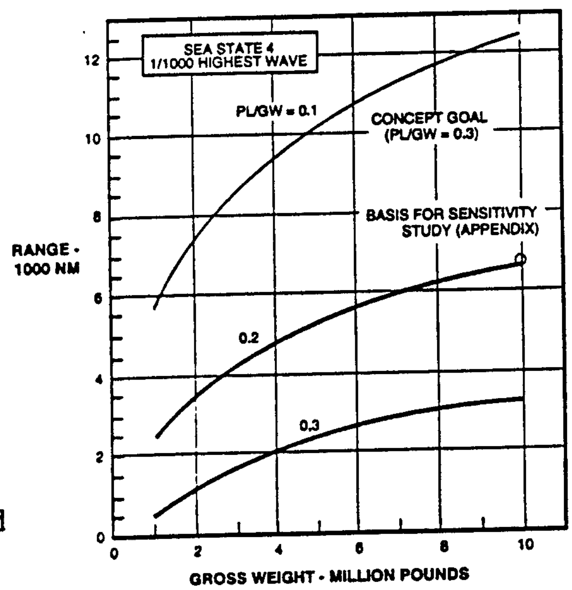

Figure 6.1.2.1-1
Parametric Sizing Results

The concept has a goal of 10,000 miles with a .3 payload fraction--about three times the parametric result.

The aerodynamic efficiency (lift-to-drag ratio) of these vehicles is shown in Figure 6.1.2.1-2a. This parametric is very sensitive to wing height-to-wing span ratio which is shown for reference in the Figure 6.1.2.1-2b with values of h/b approaching .04 at the larger gross weights. Lift-to-drag ratios of 30 are attainable at these large size vehicles when over-flying a sea state 4 condition.

The blended concept produces maximum lift-to-drag ratios that agree closely with the parametric result.

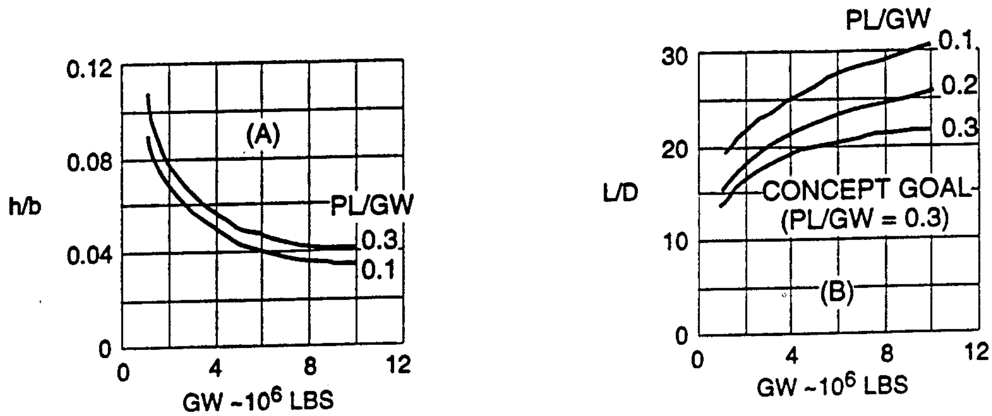

Figure 6.1.2.1-2
Parametric Sizing Characteristics

The weight empty-to-gross weight ratio (WE/GW) variation is shown in Figure 6.1.2.1-3. Values of .35 to .55 are representative of current Russian size vehicles with values of .31 to .45 for the larger vehicles.

Generally, the vehicles with larger payload fractions have larger empty weight fractions because payload tends to produce concentrated loads thus requiring additional structure whereas fuel can be placed to minimize requirements for additional structure. The blended wing-body concept empty weight fraction goal is about two thirds of parametric value.

Cruise Mach number at a typical mid-point weight as shown in Figure 6.1.2.1-4 varies between .51 and .57. For flight at constant C_L (study assumption), the cruise Mach number decreases as vehicle weight decreases due to fuel burn-off. The larger size vehicles optimize for maximum range at a slightly higher speed than for the smaller vehicles. Optimum speed also depends significantly on the payload fraction which determines the available fuel-to-gross-weight ratio and range capability.

The concept has a cruise speed goal about 10% higher than the parametrics suggest for maximum range.

As discussed earlier, a significant mismatch between the number of engines required for takeoff and cruise occurs for these vehicles. Figure 6.1.2.1-5 illustrates this mismatch. For example, a vehicle with a design payload fraction of .30 requires 20 engines of the P&W 4084 size for takeoff and only 10 for cruising at the specified design conditions. At cruise, the remaining engines operate with feathered fan blades.

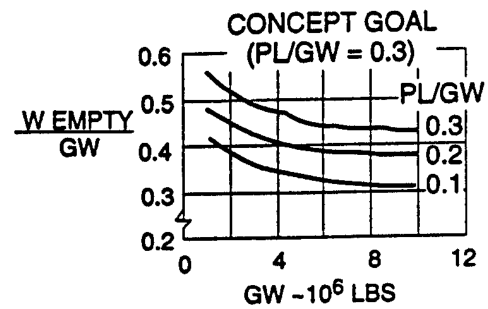

Figure 6.1.2.1-3

6.2 Operational Issues

The operation and resulting performance of wingships not only depends on technical issues related to the design and engineering of the wingships, but also on how the wingship is interrelated with its infrastructure, traffic management, weather conditions, and reliability, maintainability and availability. The operational issues and their input on wingship performance are important considerations discussed below.

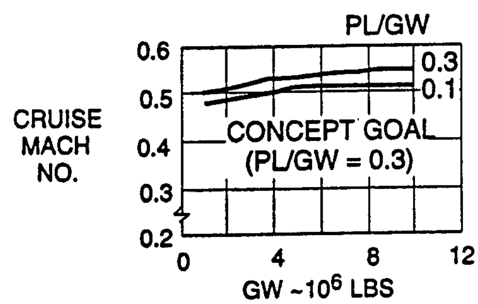

Figure 6.1.2.1-4

6.2.1 Infrastructure

Introduction of wingships to military or commercial operations may require that significant infrastructure be in place. Some will require only modification of existing facilities and procedures, while others may be quite complex and expensive. The necessary infrastructure can be described in three broad categories of Basing, Operating, and Maintenance.

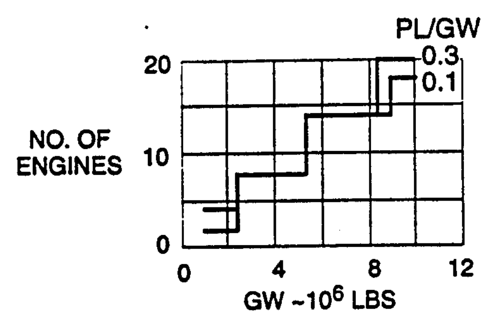

Figure 6.1.2.1-5

The basing is essentially the same as that currently in place; modification or extension of such things as crew support facilities, training courses and facilities, supply warehousing, and intermediate maintenance facilities must be accomplished. Berthing and mooring arrangements may require significant construction projects. Design and construction of piers with movable fingers, or causeways, may be needed to allow access to wingship doors and hatches.

Additional infrastructure required by operational considerations may be extensive, depending on what mission(s) the wingship performs. Fueling while away from home port is necessary for all missions. To take advantage of the wingship's speed, it will be necessary to have fueling capability in place for any route the particular mission may follow. Surface ships could station themselves along the way, but the time required for them to take station may slow the mission, even if they speed to their stations during the few days at the start of the campaign while cargoes are staging and loading on the wingships. Land base fueling is possible but requires host-nation-agreement and would probably not be on a direct route, thus slowing the mission.

The ability of wingships to land and loiter on the surface lends much flexibility to their concept of operations. It may complicate the performance of pre-flight checks necessary prior to takeoff from any site other than home base though. Inspection of external appendages and operating devices will be difficult; it will be dangerous in rough weather.

Perhaps the most complex infrastructure additions are those required for the transport mission. Special cargo handing equipment and procedures will be needed in the ports of embarkation and at the point of discharge, in both well developed and undeveloped areas. Ramps, causeways, cranes to deploy them, and other devices to allow transition from wingship to shore will be necessary.

Maintenance requirements will dictate that large investment be made in wingship-related infrastructure. Drydocking will be required for vehicles the size of the large wingship concept. The wingspans being discussed will make it necessary to acquire floating drydocks with no, or very low, wing-walls. Existing waterborne hull-cleaning techniques will be useful, but since wingships will probably not have anti-fouling marine hull coating, (due to the high weight of such coating) cleaning will be required much more often. Engine maintenance, change-out, and repair will be a demanding issue, more so than for conventional aircraft since the wingship will be waterborne, often at unimproved sites. This will require either the wingship to have self contained spares and change-out equipment and a large uncommitted weight penalty, or the existence of other wingships serving as "Tenders," deploying with the lift mission.

The subject of infrastructure must be covered in much more depth than this early phase has allowed. If the concept is developed further, the technical design, concept of operations, and required infrastructure must be defined in an integrated balanced fashion.

6.2.2 Traffic Management

If wingships are to serve in the strategic surge sealift mode, they will have to operate in crowded, and in some cases restricted, traffic areas. While the ports of debarkation, or destination, cannot be precisely known, the ports of embarkation are known. More detailed investigations than this study has included are needed, but it is known that very large wingships will present traffic management problems while entering and leaving port, and perhaps in the takeoff and landing areas. Some ports used for military cargos may not be accessible by the very large wingship concepts being discussed, others will require that the channel, or river leading to the port be closed to all traffic other than the wingship while it transits from/to landing area.

Clearing and keeping the takeoff landing areas clear will be mandatory. Selection of the takeoff landing sites may require a detailed trade-off analysis of issues such as taxi distance to or from port, traffic density in the area, size of the takeoff/landing area, prevailing wind, tide, and current, and effort required to keep the area clear. It must also be determined what effect the presence of wingships has on other vital traffic in the area.

6.2.3 Rogue Wave Detection And Avoidance

One of the most serious threats to wingship operation in open ocean areas of the world are the so-called rogue waves. Such waves are not the norm, but they have to be considered as a definite threat to any vehicle operating close to the ocean surface. The most likely locations for the formation of rogue waves during storms, based on observations, are the North Atlantic, the Norwegian Sea, the Gulf of Alaska and the Weddell Sea (Antarctica).

Rogue waves can build up within 12 to 24 hours to wave heights from about three times the normal significant wave height of a certain sea state in a storm up to a wave height of 100 feet, and 200 feet in extreme cases. Such waves are a combination of large swells and large waves of the

same storm system or two different storm systems. The energy spectrum of these extremely large waves is simply the sum of the spectra of the swells and the superimposed waves.

Some preliminary investigations were made with regard to the early detection of rogue waves and their possible avoidance by a wingship. It was found that an early detection may be possible by the use of more sophisticated radar systems using the "pulse compression technique." A number of cases were calculated in order to get some idea if such systems could be used for our purposes. Using realistic antenna heights above sea level and estimated wingship/wave closing speeds, it appears the resulting early warning times are sufficient to avoid collision with rogue waves.

Nevertheless, it is strongly recommended that further investigations be made in conjunction with the manufacturers of such early detection systems. The Russians have made studies of flying over obstacles, such as islands, with cruise power only. They claim that it is possible. Investigations have to be made with regard to climbing time and distance in order to avoid rogue wave collisions.

6.2.4 Reliability, Maintainability And Availability

The following issues, largely propulsion oriented, have major implications for the RM&A aspects of operational wingships that transcend it's technical features. Each is discussed separately below and also in Appendix L.

1. **Fuel flexibility** - to help achieve high availability via good integration with naval vessels in a task force as well as port facilities, it is recommended that operational wingships be capable of using diesel fuel marine (DFM) as their primary fuel. The concern is that high grade JP is not normally available in large quantities (a 10,000,000 wingship would require 3-4,000,000 lbs/500-650,000 gallons) to totally refuel. It needs to be more in common with the bulk fuel users at sea which are ships. NAVSEA has done the modest engineering development work on every marinized aircraft engine it uses for main ship propulsion which includes fuel heaters for cold weather starting and water washers to remove alkali metals and Vanadium which would corrode the turbine. DFM is also less of a fire hazard and is cheaper. NAVAIR (AIR 536) has demonstrated a strong predilection towards restricting the operational fuel of both jet and diesel engines under its development cognizance to high quality jet fuels (JP5). This arrangement is decidedly not attractive for wingship engines. The Russians concurred immediately on this topic,

even though they too were using JP for their development ekranoplans. The recommendation is that we plan today on using JP for vehicle development but also plan on the modest development needed to convert them all over to DFM for operational use, with JP as an alternative fuel, not the primary.

2. **Engine water washing** - Flight operations 20 feet off the waves will experience about 3 times the sea salt in air concentration that carrier deck operations at 60 feet or so will produce. Consequently, there will be a rapid loss of both stall margin and EGT margin from ingested sea salt. Relatively frequent engine (mostly core) water washing to remove these salt deposits will be mandatory. The present Russian ekranoplan gas turbine engine water wash interval is after every flight. ASW helos wash after each flight. Present US fleet and commercial water washing are tedious and would be totally unsatisfactory for wingships. Using current practices, a wingship would spend as much time washing engines as it would flying. The resultant loss in availability would be at least 50%. Study of this problem in the US before the 9/93 Russian visit suggested that very little had to be "invented" to solve this problem. The practices that would need to be used to effect a wash of all engines in under one hour (while loading or unloading so the down time would count against that and not "Maintenance") are as follows:

a. Engines and airframe equipment (sensors and cabin bleeds) must not require pre-wash disconnects and post-wash connects or the closure of bleed systems from outside the aircraft.

b. Instead of using a starter air cart hooked up to each engine starter, one at a time, use airframe mounted APUs and a single manifold of pressurized air to each starter to permit all to be motored over during a wash at the same time (as the Russians do now). Keep engine cross bleeds closed, as is done today.

c. Reduce starter supply air pressure and motor the engines over continuously at 18% or so RPM, not the usual 30-33% which quickly overheats starters and forces 5-30 minute delays waiting for them to cool. The Russians do this now.

d. Use water wash probes built into the core and fan in lieu of external wash systems or major disconnects to anti-ice systems to inject wash water. The Russians said this was being designed for the LUN as we were speaking about it.

e. Build the system for use by two crew members - one on the wingship controlling the whole operation from a single panel and one on the dock to hook up the water or water/alcohol mix in winter.

f. Use an on-board engine diagnostic system to determine when a wash is needed in terms of EGT, fuel flow, or speed match changes as the Russians plan to do. The Russian operational goal (yet to be tried or achieved) is one wash every 100-200 hours, depending upon ingestion severity. US utility gas turbines use such systems today to define the interval from dirt/salt/smog and moisture ingestion.

g. Be prepared for large quantities of fresh potable water when washing - possibly on the order of 65 gallons for the core in a 100K thrust class engine when one wash and one rinse is needed. Assume half when just rinsing. Wash with wash solvent only every 60 hours or so but rinse daily if needed. The fan might take up to 240 gallons of water for a wash and rinse, half that for just a rinse. These are not firm requirements and need to be developed by engine stand and operational testing. The Russians felt that in a real emergency at sea, even sea water could be used.

3. **Engine effects on vehicle availability** - the Russians currently remove and replace all engines every 500 vehicle hours, which on an 8 engined LUN equates to 2 ERs/1000 engine hours. (Their operations are only about 100 hours/year which are typical of a development vehicle but low for an operational one.) In 1991 the USN aircraft values ranged from 0.2 to 2.6 with the fleet average being 1.2 ERs/1000 engine hours. This places the Russian values midway between our average and our worst. The most significant fact of their statistics is that eventually they change engines as a group, and do not try to keep them on the wing. This is likely to help their operational personnel substantially in keeping availability up. We should plan on doing the same thing and altering AIR 04 policies of doing only on-condition maintenance as the airlines do. This also takes the recognition that the support chain for a wingship would see not just periodic engine repair costs every year as a "baseload" of maintenance and parts replenishment needs but also a "peak" as well in the year of a major change of all engines. Our scheme of supportability for wingships may therefore have to be more in line with ships and not aircraft.

NAVAIR's engine reliability values for the entire fleet by aircraft type and engine model for 1991 were examined. This was done to determine any adverse impact on availability,A(o), to be expected by using a large number of engines - say 10 to 20. The Russians said 8 was enough and

10 was about as much as they would ever wish to deal with. The USN statistics suggested the following:

- 20 engines vs 8 need only cost about 5% in A(o)
- immaturity in engine development would cost about 7% in A(o)
- poor integration into the logistic chain would cost 18% A(o)
- virtually no logistic support would cost 40% in lost A(o)

Properly treated, wingship availability as far as engines was concerned might be as high as 80%. The prime contributor to lost availability was down time waiting for parts, which is likely tied directly to mission need.

7. Mission Analysis

In addition to the evaluation of wingship technical feasibility, a Wingship Mission Analysis Team (WMAT) was formed to identify and evaluate potential military and commercial applications. The WMAT is made up of government and industry analysts and engineers with broad experience in aircraft design, ship design, construction, and operations. Team members also have analytical backgrounds in military transportation and combat operations, as well as knowledge of commercial considerations. This section describes the efforts of the Wingship Mission Analysis Team.

7.1 Mission Analysis Objectives

The primary objective of the Mission Analysis was to assess the utility of wingships in military missions which might require or benefit from their use. It was first necessary to identify and catalogue the most promising potential wingship military missions.

A secondary objective was to provide an initial economic analysis of wingships, and to roughly compare the cost effectiveness of wingships to alternative platforms performing the same missions.

A third objective was to provide an exploratory survey of potentially promising commercial applications for wingships. This objective was established with the assumption that wingships may prove commercially viable, and that development of such vehicles will only proceed if there is justification from both military and commercial perspectives.

7.2 Mission Analysis Team Membership, Interfaces And Support

This mission analysis section of the Wingship Investigation Final Report is a compilation of several independent projects undertaken by the members of the WMAT. Reports of each project are included as appendices.

The WMAT was formed from government and private industry. The team was headed by Carderock Division/Naval Surface Warfare Center (CD/NSWC) and included representatives from the Naval Air Warfare Center, Aircraft Division, Warminster (NAWCADWAR); Naval Surface Warfare Center, Dahlgren Division, White Oak Detachment (NSWCWO); Military Traffic

Management Command, Transportation Engineering Agency (MTMCTEA); U.S. Air Force Aeronautical Systems Center, Development Planning Directorate (ASC/XR); BDM Federal Inc.; Lockheed Aeronautical Systems Company; and Decision Science Applications Inc. (DSA).

Additional support was provided by Northrop Corporation, U.S. Central Command (USCENTCOM), U.S. Special Operations Command (USSOCOM), U.S. Transportation Command (USTRANSCOM), and the Naval Post-Graduate School Aeronautical and Astronautical Department.

7.3 Approach

In order to assess the utility of wingships through operational modeling and cost analysis, it was necessary to define the physical and operational characteristics for specific wingship concepts. Three concepts were considered:

- An **800 ton "Russian style" wingship conceptual design** provided by Northrop and reflecting existing Russian wingship geometry and philosophy. A two-view presentation is shown in Figure 7.3-1.

  Speed: 330 knots
  Payload/Range (Payload Fraction): 160 tons/2900 nm (0.2)

- An **Advanced 5000-ton Aerocon wingship** utilizing advanced materials and structural methods is shown in Figure 7.3-2.

  Speed: 400 knots
  Payload/Range (Payload Fraction): 1725 tons/9000 nm (0.35)

- A **3000-ton Transitional wingship** variant of the Northrop model developed by ASC to represent a transitional vehicle intermediate between the smaller "Russian-style" wingship and the Aerocon concept.

  Speed: 320 knots
  Payload/Range (Payload Fraction): 600 tons/4600 nm (0.2)
  900 tons/2050 nm (0.3)

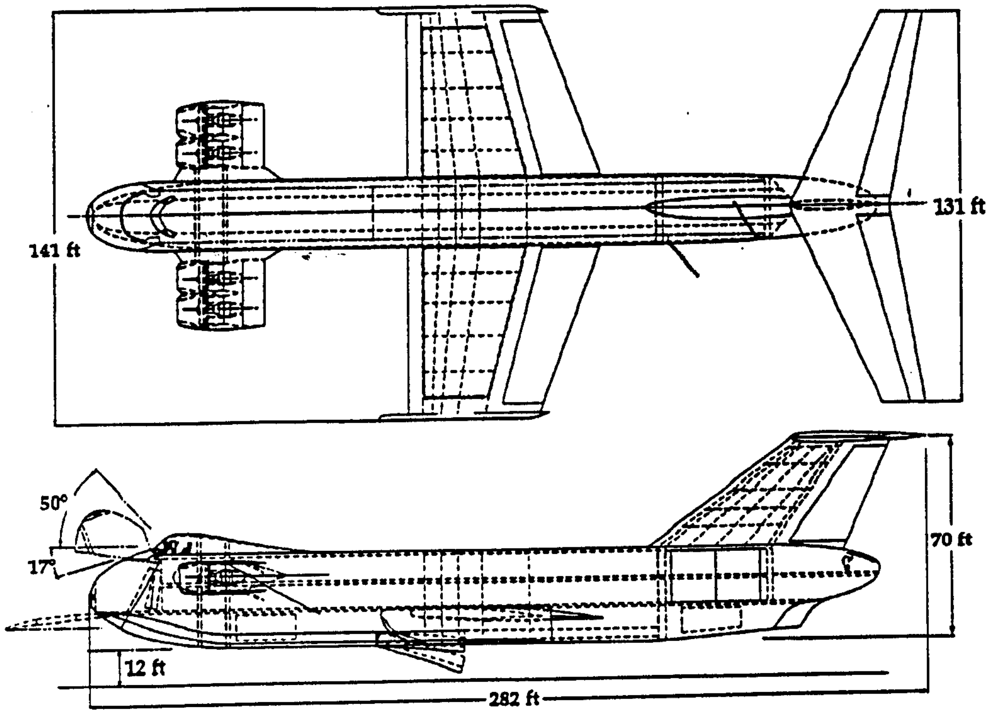

Figure 7.3-1 800 ton "Russian style" Wingship

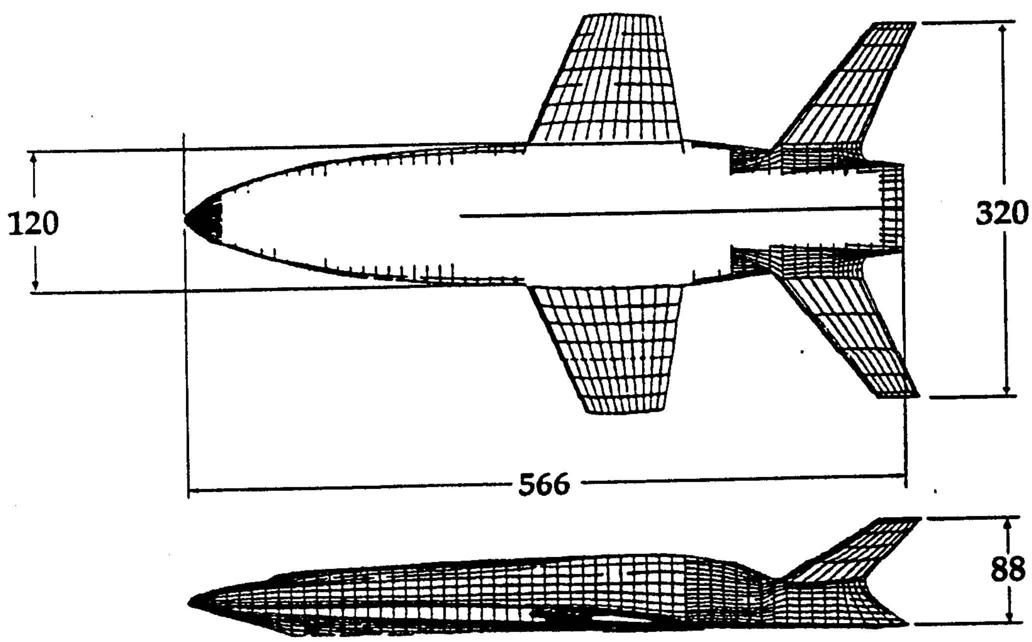

Figure 7.3-2 5000 ton AEROCON Wingship

These conceptual designs were not subjected to rigorous feasibility analyses and their operational characteristics may be somewhat optimistic. The 800 ton wingship design was based on existing technology and the given performance characteristics are probably reasonable.

As preliminary mission analysis was being completed, Aerocon, Inc., provided a description of the DASH 1.6 cargo variant Wingship. WTET members audited the performance predictions of this vehicle and calculated its range to be 3,500 miles rather than 9,000 miles as shown on page 7-2. The performance and life cycle cost of this "audited concept" were estimated as an excursion to the primary analysis and are discussed later in this report.

The WMAT catalogued a range of theoretically possible military applications for wingships, including both lift and combat roles. The team then investigated the utility of the appropriate wingship concepts in the military missions using combat modeling simulations, defense transportation analysis, and military mission analysis. The WMAT also conducted exploratory surveys of commercial applications for wingships through "brain-storming" sessions.

Several assumptions were made to simplify the analysis:

- Transport design loads permitted for wingships, while current assets restricted to allowable cabin loads.

- Utilization rate of 24 hours for wingships, 12 hours for current air assets.

- Perfect reliability and maintainability for wingships.

- All required infrastructure and operational procedures for Wingship in place and effective without additional cost.

If the wingship concept is not clearly superior, given its preferential treatment, then it should not be considered seriously as an alternative to conventional concepts.

The WMAT performed an initial estimate of the costs required to develop, procure, and operate the 3,000-ton and 5,000-ton wingships using several different aircraft costing models. Appropriate measures of effectiveness were developed and the wingships were compared to other transport platforms. All cost estimates and comparisons were based on <u>very</u> limited wingship design data, technical characteristics, operational performance, and concepts of operation.

7.4 Military Applications Examined

The military applications examined fell into two traditional categories: transportation and combat. Russian developmental work on wingships did not have long-range transportation as one of its objectives, but recently they have been advocated for such roles. Much of the WMAT's efforts were expended analyzing wingships in potential military transportation missions. The missions were classified into three types: strategic heavy lift, rapid insertion lift, and amphibious assault.

7.4.1 Military Transportation Applications

In a strategic heavy lift mission, a fleet of wingships would be used to transport combat and support units into a theater as required by contingency plans, essentially replacing/augmenting current strategic lift aircraft, such as C-5s, and maritime shipping, such as large, medium speed Roll-on/Roll-off (ROROs) ships (LMSRs). To assess this mission, the WMAT conducted a deployability analysis comparing the force closure times necessary to move various Army units into a scenario. Transportation assets for this analysis included both wingships and projected conventional assets for the year 2005. The analysis included an initial operational and cost comparison of wingships to conventional transportation assets performing the same lift missions.

The WMAT assessed the utility of wingships in transporting the following forces to Southwest Asia or North East Asia scenarios with the exception of the separate mechanized brigade which was transported to the Caribbean:

- MRC-East Strategic Mobility Requirements
- Notional Corps (three Divisions, one Armored Cavalry Regiment, & Corps Support)
- Two Heavy Mechanized Infantry Divisions
- One Heavy Mechanized Infantry and one Airborne Division
- One Airborne Division
- Separate Mechanized Brigade
- One Armored Cavalry Regiment
- One Marine Expeditionary Brigade (MEB)
- 10k Early Entry Force
- Patriot air defense brigade
- Critical Units (Patriot, THAAD, USMC Point Defense, and MLRS/ATACMS batteries)
- 2k Early Entry Force

In a rapid insertion lift mission, wingships would be used to rapidly insert ground forces and/or supporting smart, force-multiplier weapon systems, such as MLRS/ATACMS, Patriot, and THAAD, into a conflict much earlier than possible with conventional lift. The WMAT conducted analysis of the operational military benefits that could be gained by the early entry of such forces into a conflict.

Wingships could be used to conduct amphibious operations by transporting Marine expeditionary forces (MEF, MEB, MEU) either directly to a landing zone, or to conventional amphibious assault ships already deployed in the area. A detailed analysis of this mission has not been performed.

7.4.2 Combat Applications

A smaller wingship (800 tons) fitted with appropriate sensors and weapon systems could feasibly perform a variety of combat missions. The WMAT conducted initial assessments of the operational advantages and disadvantages of combat-configured wingships in various scenarios and concepts of operation. In most combat cases, the wingships would perform the same mission as an existing conventional platform, but with considerably greater platform speed. Analyses of wingships in these roles required a large number of assumptions about the platforms' technical capabilities and performance characteristics.

Strike/Land-Attack Operations: Wingships could be fitted with land attack cruise missiles or Naval Tactical Missile Systems (NTACMS) to perform strike and land attack (e.g. anti-armor) operations.

Theater Air and Ballistic Missile Defense: Wingships could be fitted with radar and missile systems to provide theater air and missile defense for ground forces and installations ashore, and/or naval surface groups afloat.

Mine Warfare: Wingships could be used to rapidly transport airborne MCM equipment to a theater, and/or to serve as airborne MCM/minelaying platforms for use in open water areas and in advance of an amphibious operation.

Special Operations Warfare: Wingships could be used to rapidly insert and retrieve special operations forces (SOF).

Anti-Submarine Warfare: Wingships could be fitted with appropriate anti-submarine warfare (ASW) sensors and weapons to perform airborne ASW missions.

7.5 Wingship Lift Findings And Indications

7.5.1 Force Closure And Rapid Insertion

Compared to assets projected to be in the inventory in 2005, large transport Wingships do not appreciably improve the closure of, heavy Army forces to distant scenarios. Figure 7.5-1 presents closure curves (calculated using MTMC's JFAST model) for the deployment of a notional corps to SWA. The conventional airlift and sealift assets projected for 2005 close the corps in C+31 days. A fleet of twenty-three 5,000-ton wingships, used in place of the RORO ships, closes the corps at C+30. In general, the performance of moderately sized fleets of Wingships is only marginally better than conventional transport assets for delivery of various sized forces. A larger fleet of 63 wingships would close the corps sooner, but would be prohibitively expensive to acquire, operate, and maintain. Major improvements in force closure require unaffordably large fleets of wingships. Figure 7.5-2 presents comparisons of closure times of various forces.

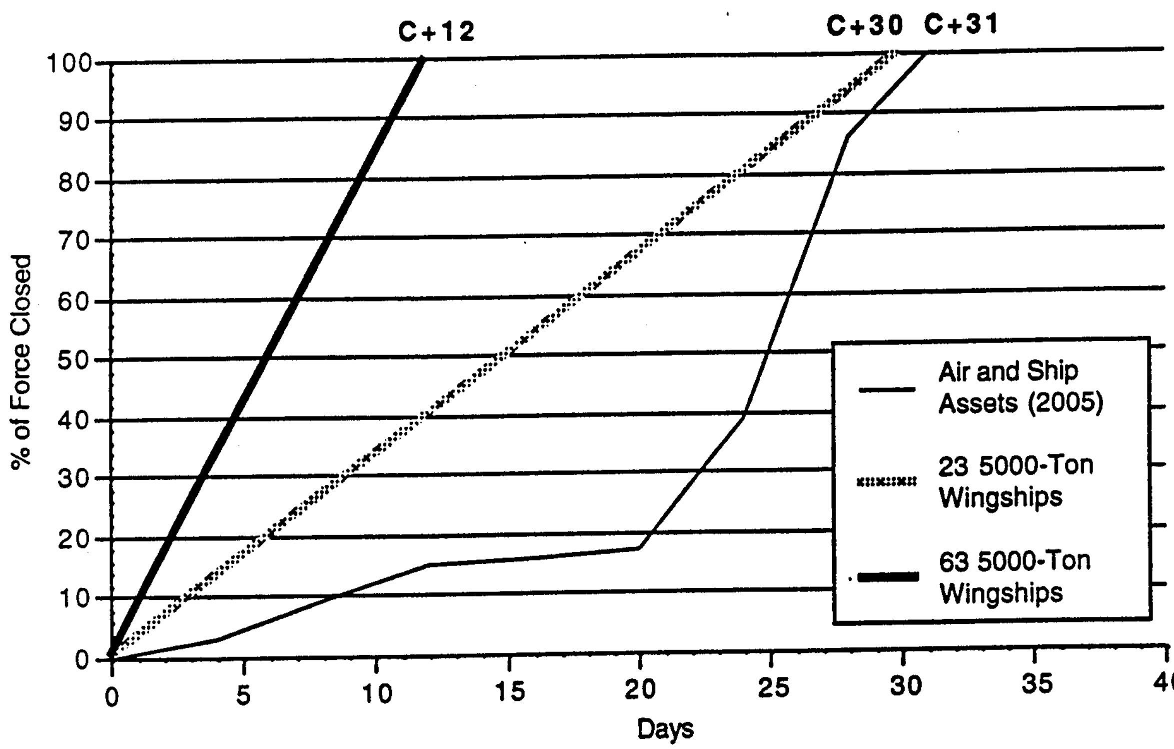

Figure 7.5-1
Force Closure, Notional Corps to SWA

Force	Number of Wingships	Time (Days) to Close 2005 Assets	Time (Days) to Close Aerocon Wingship	Days Saved
Corps to SWA	23 63	31	30 12	1 19
2 Divs to NEA	13 41	27	19 8	8 19
Mech Brig to Carribean	2 8	9*	8 2	1 7
10K to SWA	6 16	16*	14 4	2 12
2K to SWA	4 6	6*	6 4	0 2

* Airlift Only

Figure 7.5-2
Force Closure Comparisons

In a confrontation as outlined in the DoD Mobility Requirements Study's (MRS) Southwest Asia (SWA) Major Regional Contingency (MRC), conventional airlift will transport light units and pre-positioned ships will move the equipment of some heavy units in the first two weeks, but the first ships carrying heavy Army divisions will not begin arriving until 27 days after C-day (the day when units receive orders to move from their CONUS bases to the combat theater). Until heavy divisions arrive, only light and expeditionary forces will be in place to hold back an enemy advance. Defending light U.S. forces would receive significant casualties in the first three weeks if faced with an organized advance of multiple enemy heavy divisions supported by aircraft and tactical missiles. If enemy forces successfully target and capture or damage the port and airbase facilities which the U.S. plans to use for reinforcement, the insertion of adequate combat power to drive the enemy back would be drastically more difficult and dangerous.

A closer examination of Fig 7.5-1, noting that the Wingships do deliver more equipment in the early phase than conventional assets would indicate that platforms with the speed and capacity of wingships could be used to rapidly insert some heavy ground forces and lethal weapon systems into the theater within the first two to three weeks of the confrontation. Successful insertion of the right forces and weapons could significantly delay the advance of enemy forces and reduce U.S. casualties. Such an insertion could prove critical to the successful defense of the ports and airfields necessary for reinforcement.

7.5.1.1 Conventional Regional Deterrence

The ability to use fast, heavy lift wingship platforms to transport significant forces to any coast on short notice could serve as a military deterrent to regional hostilities. A successful wingship could be a unique vehicle for rapidly delivering large quantities of all types of current or future U.S. mobile ground equipment. A potential aggressor, in all likelihood, will be deterred from using force to achieve strategic goals, knowing that the U.S. can swiftly deploy major forces to stop aggression. The benefit for savings in both lives and resources of such deterrence cannot be quantified.

Any U.S. military unit that is trained, equipped, and ready to deploy from a wingship point of departure is, in essence, "forward deployed." The ability to rapidly deploy forces could be demonstrated in exercises and operations so that it would be known and appreciated worldwide.

The full potential of the wingship is unknown; in the mind of a future enemy, it's capabilities are even less understood. In a future contest with U.S. wingships involved, the outcome for an enemy becomes very uncertain and unattractive. If the wingship concept could play a significant part in the deterrence of just one shooting war, it's value would be large. A wingship program that proceeds toward further study and formulation can be of value in deterrence even if it never goes to production. An example of this is the U.S. SDI program and it's effect on the Soviet military.

7.5.1.2 Lethal Systems - Air Defense, MLRS/ATACMS

In a simulation of a SWA scenario, wingships were shown to be of significant value in rapidly inserting precision-guided, force-multiplier defensive and offensive systems into the early weeks of the hostility. Modern air defense systems, including Patriot for theater defense against aircraft and SRBMs, Theater High Altitude Air Defense (THAAD) systems for theater defense against MRBMs, and LAV-AD for defense of expeditionary forces against helicopters, could be critical to defending ground forces against attacking aircraft and tactical missiles. Initial assessments indicate that just a few fast, heavy-lift wingships could rapidly deliver significant air defense assets to help a light force defend itself against enemy aircraft and missiles. Such a defense could very well prove critical to the success of the light forces pending the arrival of heavier divisions.

Modern deep strike weapon systems, including the Army Tactical Missiles (ATACMS) armed with smart submunitions, can provide a significant leverage for ground forces. Preliminary analysis shows that batteries of MLRS equipped with ATACMS missiles could be rapidly delivered by

wingships into a theater to support U.S. defending forces. These weapons would allow light U.S. forces to defend successfully against enemy armor divisions pending the arrival of heavy forces. The ATACMS systems leveraged in this way could result in far fewer U.S. casualties and make a significant difference in the course of the war.

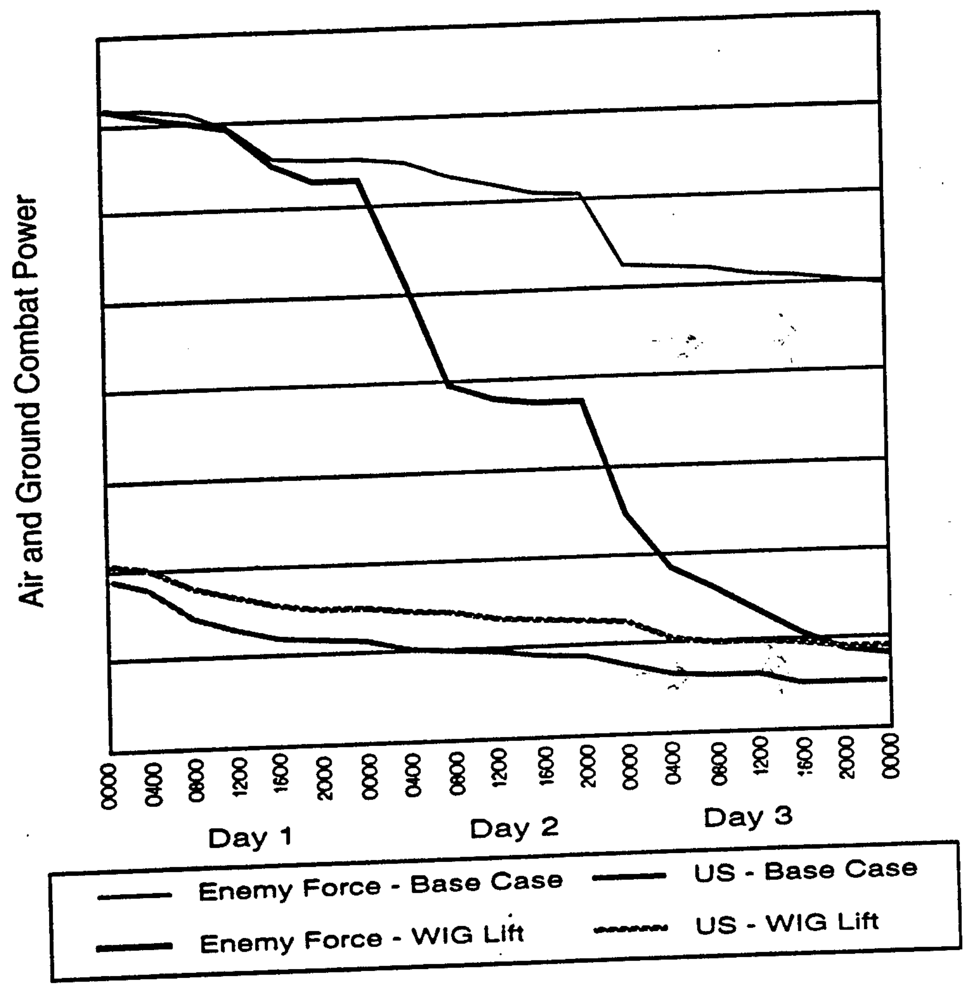

Figure 7.5-3
Combat Power Comparison in SWA Scenario

Figure 7.5-3 presents results from the simulation of a SWA scenario using BDM's METRIC model. The figure compares combat power of U.S. and enemy combat forces for a base case and an excursion in which three 3000 ton wingships are used to insert small units of MLRS/ATACMs (18 launchers), THAAD (9 launchers), Patriot (8 launchers), and LAV-AD (24 vehicles) in the

initial days of the battle (during this phase, overwhelming enemy forces are advancing on light U.S. forces in defensive positions). Defending U.S. forces were able to use the additional air defense and anti-armor weapon systems with great effectiveness, resulting in fewer friendly casualties and significantly increased enemy attrition.

7.5.1.3 Prepositioned Assets in Nearly Simultaneous Contingencies

The ability to use fast, heavy-lift wingship platforms may provide a true capability to transport prepositioned assets successfully in nearly simultaneous or sequential contingencies. Current and programmed transportation assets cannot fully support the requirement to fight multiple regional contingencies - this discrepancy could be eliminated with a fleet of fast, heavy-lift wingships. A platform that could withdraw forces from one contingency and rapidly deploy them into another would provide a new, unique U.S. strategic capability.

7.5.1.4 Value When NBC Weapons Used on Air / Sea Ports

The potential capability of wingships to off-load equipment and troops onto a beach may be utilized to transport assets into or out of a theater when nuclear, biological, or chemical (NBC) weapons have shut down the air and sea ports. NBC weapons are proliferating and the possibility that an enemy may use them in future conflicts is high. Theoretically, an enemy could use NBC weapons to destroy or contaminate critical transportation destination points, including airfields and sea ports, thus severely degrading our capability to lift military forces into the theater. An appropriately designed wingship would not be constrained to off loading at established port facilities, and it could successfully deliver large amounts of heavy equipment onto a suitably prepared beach. Movement of forces out of the beachhead could, however, be a problem without a nearby transportation infrastructure.

7.6 Wingship Combatant Findings / Indications

7.6.1 Naval Mine Warfare

Wingship platforms show significant promise in the area of airborne mine countermeasure (AMCM) warfare. There is a requirement to deploy mine countermeasure (MCM) platforms and systems overseas in sufficient quantities to clear all mines from an assigned area or to keep the threat of mines to traffic as low as possible. A critical area of interest is in coastal shallow waters. Currently, the air portion of the MCM mission involves the transport of an AMCM squadron to the

theater by transport aircraft (seven C-5s and eight C-141s), followed by the employment of helicopters to conduct the MCM operations. The loading and off loading of equipment is very time-consuming, and often takes place at significant distances from the operating area.

A wingship could be dedicated to MCM missions, rapidly delivering an AMCM squadron directly from CONUS to the operating area. The wingship could also be fitted to act as the AMCM squadron base for helicopters and/or Remote-Operated Minecraft Aircushion (ROMAC) vehicles). The wingship could itself use MCM sensors and clearing systems to detect and destroy mines in shallow waters, and could be utilized for clearing mines in advance of amphibious operations.

7.6.2 NTACMS Variant vs. Massed Maneuver Forces

Wingships show promise for the employment of the Naval Tactical Missile System (NTACMS), a sea-launched version of the Army's ATACMS. A smaller wingship fitted with missile launch cells carrying NTACMS missiles could be rapidly deployed to support early entry U.S. forces. The wingship could carry its own unmanned aerial vehicle (UAV) sensor for targeting, and/or could operate in an overall deep strike architecture, utilizing sensing and targeting data from external sources as illustrated in Figure 7.6-1. The wingship could be very effective at destroying massed maneuver forces within approximately 100 km of the coast. This support may be necessary to help early entry U.S. forces fight superior enemy forces and defend the port facilities that will later be used for the off load of reinforcements.

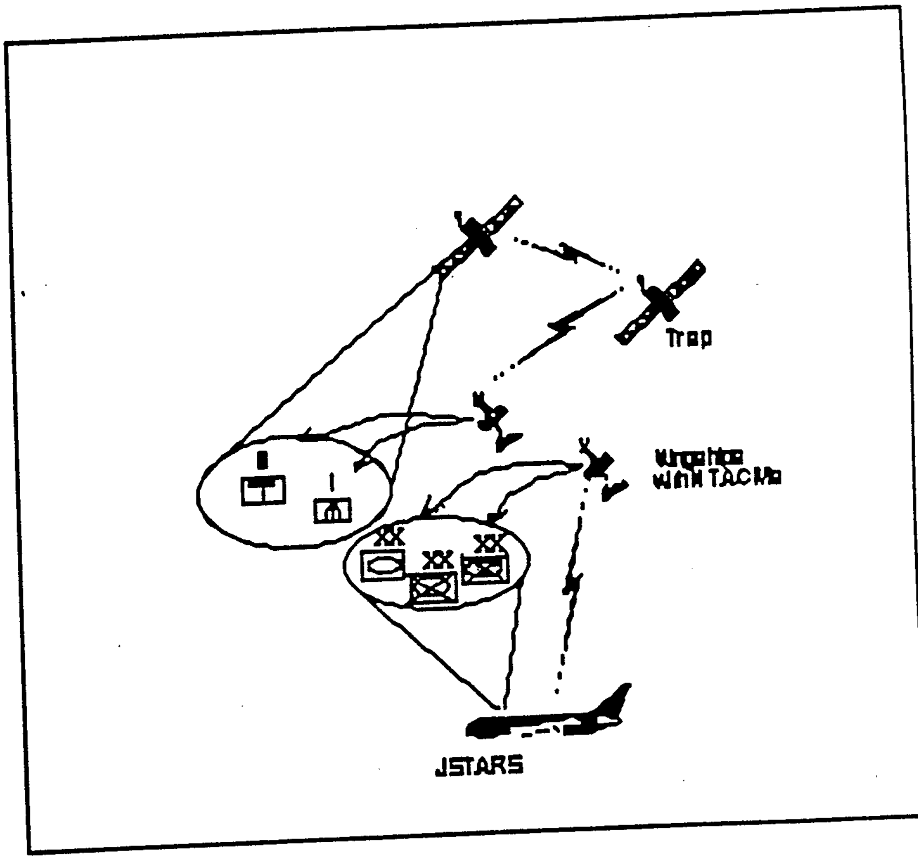

Figure 7.6-1
Combat Wingships with NTACMS

7.6.3 Strike Warfare

Wingships show promise as strike platforms for launching land-attack cruise missiles, including Tomahawk TLAMs, SLAMs, and Tri-Service Stand-off Attack Missiles (TSSAMs). A smaller wingship fitted with missile launch cells carrying land-attack missiles could be rapidly deployed to serve as a deterrent to aggression, and to support early entry U.S. forces. The wingships could be used as the weapons-launch platforms in a future architecture for locating and destroying critical mobile targets (e.g. ballistic missile launchers) as illustrated in Figure 7.6-2.

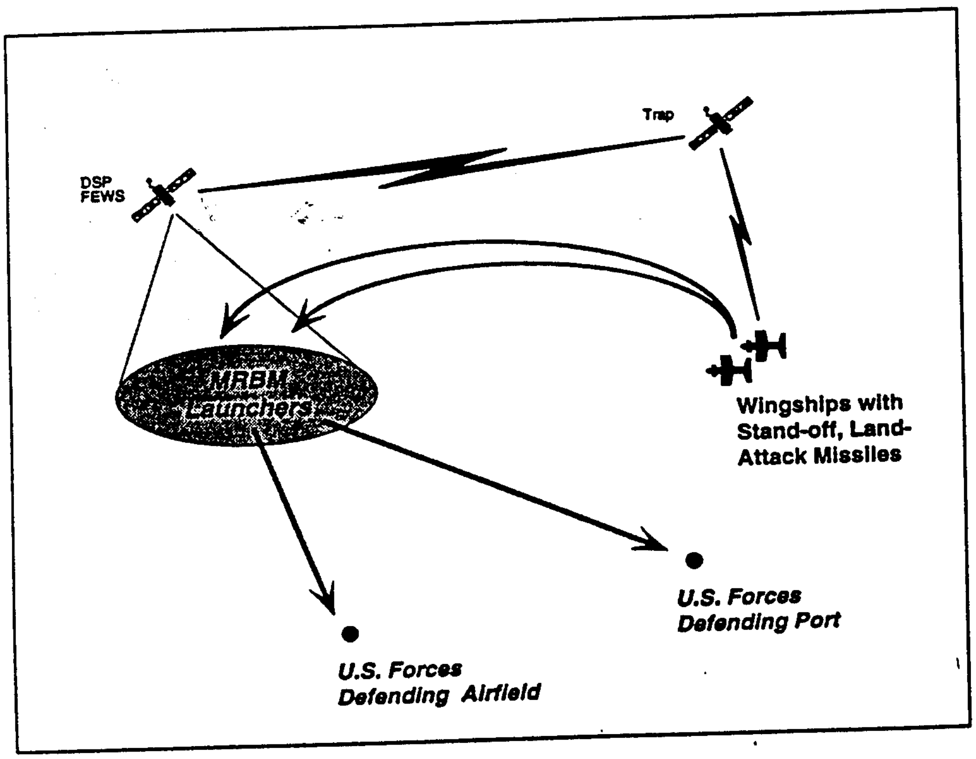

Figure 7.6-2
Combat Wingships Targeting Critical Mobile Targets with Land-Attack Missiles

Depending on the scenario, a strike warfare wingship would be conducting a mission that could be filled by a number of other alternatives, including ships, submarines, carrier-based naval aviation, and strategic bombers. Rapidly deployable wingships will have to prove themselves preferable to these other alternatives.

7.6.4 Amphibious Assault

Wingships show potential as amphibious assault platforms. By their nature, wingships can operate out of bases remote from the Amphibious Operations Area (AOA), and can deliver large amounts of men and material to the AOA in a timely manner. Depending on the concept of operation, wingships could be used to land forces directly on the beach, deploy landing craft near the beach, or simply lift troops from CONUS and then transfer them to conventional assault ships. The concept of using wingships for amphibious assaults provides a flexibility for noncommittal of forces, and an ability to commit them to optional locations as political situations dictate.

7.6.5 Theater Air Defense Capability

Wingships show potential as theater air defense platforms. A smaller wingship could be fitted with an air search radar and fire control system for targeting hostile aircraft and, possibly, short and medium range ballistic missiles (SRBM/MRBMs) in the ascent phase. This radar wingship could work with another wingship fitted with launch cells carrying surface-to-air missiles in a cooperative engagement concept, and/or could relay advanced targeting data to ground based air defense systems (e.g. Patriot or THAAD). The missile wingship could carry surface-to-air missiles capable of engaging aircraft (e.g. SM-2 Blk IV), or future missile systems for engaging SRBM/MRBMs (e.g. "marinized" THAAD or SM-2 with LEAP). With improvements in radar system design, it may be possible to integrate the radar and missile launch cells in one wingship.

The air defense wingships could be rapidly deployed overseas, possibly before the arrival of other air defense assets, to provide protection for U.S. early entry forces and critical facilities ashore. Once traditional air defense assets are moved into place, the wingships could be retained to provide a forward layer of air defense. A wingship deployed well forward of U.S. forces along over-water hostile aircraft and missile flight corridors, could detect and engage aircraft and missile threats before they enter the range of land-based defense systems co-located with the U.S. forces, as illustrated in Figure 7.6-3. This forward element of air defense would increase the probability of kill against hostile targets, which would be especially important against ballistic missiles carrying nuclear, biological, and chemical warheads.

Depending on the scenario, an air defense wingship would be conducting a mission that could be filled by a number of other alternatives, including AEGIS ships and carrier-based naval aviation. As such, rapidly deployable wingships will have to prove themselves preferable to the continuous deployment of slower surface ship-based assets overseas near potential areas of conflict.

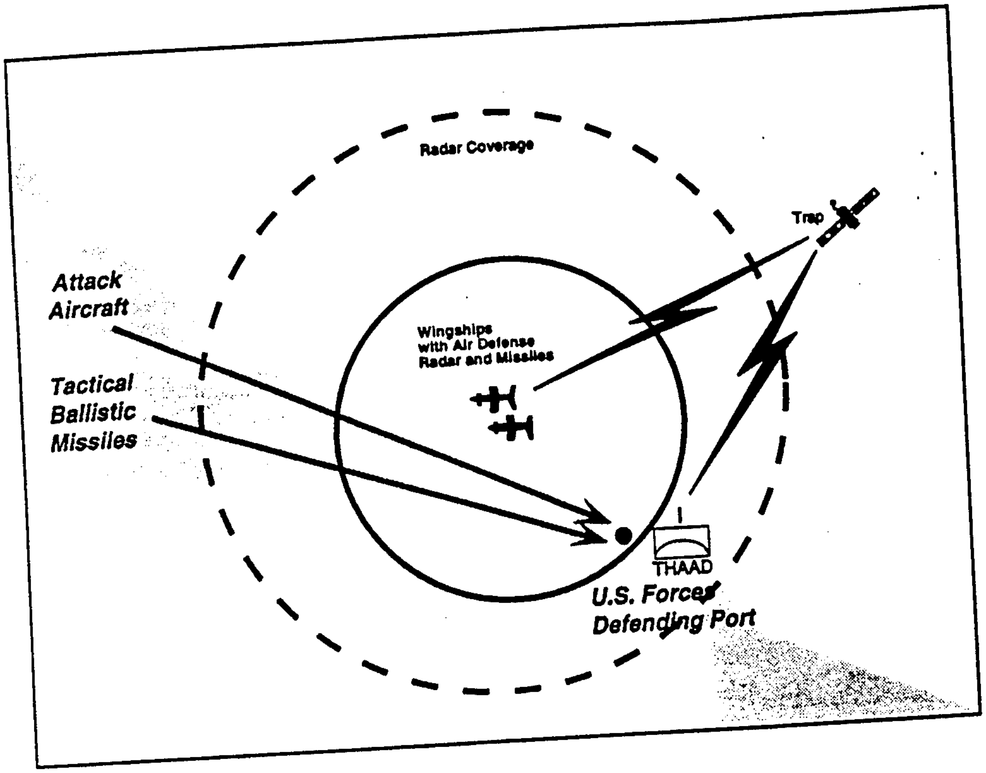

Figure 7.6-3
Combat Wingships Providing Theater Air Defense

7.7 Potential Commercial Applications

The use of wingships in commercial applications will depend on their ability to compete with other forms of transportation. Wingships must also prove themselves safe and reliable. Wingships will probably not replace sealift or airlift, but will complement ships and aircraft by providing capability to transport cargo usually carried by ships, at speeds generally associated with aircraft.

Commercial applications for wingships, certainly in early attempts at gaining market niches, will probably require smaller platforms than the large systems being considered for military lift missions. Such smaller vehicles will probably be developed in the course of a large wingship

velopment cycle. Potentially promising commercial applications for smaller commercial ingships include:

High Speed Auto Ferry

Wingships could replace existing ferries that take more than one hour to complete a crossing. They could also perform an "Auto-Train" role to carry cars and passengers long ranges between islands (e.g. Hawaiian Islands), and along coastlines.

Disaster Response

Wingships could be utilized for their amphibious capabilities to provide rapid response to natural disasters and offshore oil spills. They would be especially useful when existing transportation infrastructure is destroyed.

7.8 Wingship Costs

Rough order-of-magnitude estimates of total life-cycle costs for the 3000 ton and 5000 ton wingship concepts were developed using three different costing models. Because of very limited wingship technical data, the estimates are based a large number of assumptions about specific wingship configuration details. Among other things, the estimates assume that a lift variant airframe represents the only major hardware developmental item. The propulsion systems are assumed to be similar to the existing PW-4084, and the avionics systems are assumed to be comparable to those of current C-5s.

Cost models, by their nature, are highly dependent on concept design data. Because of the limited detail available and the optimism of the assumptions made, the cost estimates produced in this study are thought to be in the lower part of their expected bounds.

Details of the individual cost estimates can be found in the final reports of the Lockheed Aeronautical Systems Company, and the Air Force's Aeronautical Systems Center/Developmental

Planning Directorate. The cost estimates, in FY94 billions of dollars, can be summarized as follows (based on producing 30 wingships at two per year, production beginning in 2007):

Development (over 10+ years)	Tens of Billions of Dollars
Average Unit Acquisition Cost	Billions of Dollars
Life cycle Ops & Support Costs	Up to a Billion Dollars (per vehicle).

If a measure of effectiveness (MOE) of Unit-Fly-Away Cost per ton of cargo capacity is used the comparison of the Aerocon Wingship to C-5 Aircraft and Large Medium Speed Roll-on/Roll-off (LMSR) ships is as follows.

Wingship	$1.6 Million
C-5	$1.6 Million
LMSR	$ 6.0 Thousand

7.9 Cost-Performance Of WTET Audited Wingship

As mentioned in Section 7.3, the Aerocon DASH 1.6 version was closely examined by WTET members and assessed to have about half the range predicted by Aerocon. When this performance was considered, it was calculated that the effectiveness of the Wingship in strategic lift to Southwest Asia would decrease about ten percent and the lift cycle cost would increase about ten percent. These changes are attributable to the additional time spent refueling and the cost of the additional fuel used. These factors are scenario dependent, having less impact in a shorter range lift.

Figure 7.9-1 shows the results of closure comparisons for conventional assets projected for the year 2005, the Aerocon concept, and the WTET-audited Aerocon concept. Included in this table are the approximate additional life cycle costs for the wingships. Referring back to Fig 7.5-1 and using the "ball-park" cost estimated from Section 7.8, a fleet of 23 Aerocon Wingships would deliver a notional corps to the Persian Gulf one day quicker than the projected assets of 2005 at a cost increase of just over 100 Billion dollars. If the WTET performance estimates are correct, it will take one day longer at a cost of about 115 billion. Delivery of one Airborne and one Mechanized Division to the Korean Peninsula with the 5000 ton wingship will reduce the closure time by approximately one week as compared to the 2005 assets, but at a cost of about 70 to 75 billion dollars.

Force	Number of Wingships	Time (Days) to Close 2005 Assets	Time (Days) to Close Aerocon Wingship	Time (Days) to Close Audit	Days Saved Aerocon Wingship	Days Saved Audit	Approx Add'l Cost** Aerocon Wingship	Approx Add'l Cost** Audit
Corps to SWA	23 63	31	30 12	32 13	1 19	-1 18	105 210	115 230
2 Divs to NEA	13 41	27	19 8	20 9	8 19	7 18	70 150	75 160
Mech Brig to Carribean	2 8	9*	8 2	8 2	1 7	1 7	30 60	31 62
10K to SWA	6 16	16*	14 4	15 5	2 12	1 11	50 80	55 88
2K to SWA	4 6	6*	6 4	7 5	0 2	-1 1	40 50	45 55

* Airlift Only
** Assumes Retention of Conventional Assets

Figure 7.9-1
Force Closure Comparisons with Total Life-Cycle Costs

7.10 Preferred Missions

At the conclusion of the Mission Analysis described in this report, the WMAT performed a Multi-Attribute Utility Analysis to determine which applications are best suited to Wingships. The screening was based on the wingship application's support of national objectives (need, importance, frequency of mission, and technology advancement required); the probability of becoming a program (sponsor, acceptance, funding source, potential fleet size, and multiple use); and wingship competitiveness with other platforms (time efficiency, performance effectiveness, and cost). The following applications are those which ranked high.

- Strike missile combatant
- SPECOPS - Mk V SOC
- Mine Warfare
- Deep submergence recovery
- Urgent reconstitution of maritime forces
- Disaster response
- High speed auto ferry

7.11 Conclusions

The Mission Analysis conducted by the WMAT tentatively concludes that the wingship concept is of potential high value in several military applications. The missions for which the concept seems well suited are fairly narrow in scope and the vehicles must be used as part of an overall architecture, rather than in a stand-alone role. Nevertheless, the possibility of performing rapid insertion of critical equipment, mine clearing and laying, and special forces insertion in ways that are not currently possible, stirs interest in the concept.

While wingship concepts promise high value, they also carry a high price. Cost estimates included in the part of this mission analysis are based on rather sketchy data, but the consensus is that costs are reasonably defined and probably in the low end of the expected range of variation. Based on these estimates, the cost-effectiveness of wingships is predicted to be comparable to that of strategic lift aircraft, although much higher in cost per ton delivered than sealift ships.

The ambitious performance characteristic goals of the very large scale Aerocon wingship concept give it impressive predicted effectiveness. There is, however, little technical detail to build confidence that those performance characteristics are achievable. WTET estimates of likely performance of the Aerocon concept yield effectiveness reduced by ten percent and life cycle cost increased by ten percent. The concept of a very large wingship transport is too expensive for the improvement in closure times that it might achieve.

There are, as mentioned above, roles which promise value and require sizes in a range of less than one thousand tons, gross takeoff weight (GTOW). State-of-the-art aircraft designs exist in the five-hundred ton GTOW regime and Russian wingship experience reaches a similar level. A long-term approach that closely examines the possibilities of applications, military, civil or commercial, in that size range, aimed at scaling up, by a factor of two, to a military vehicle of nearly one thousand tons GTOW, will allow careful consideration of the technical and cost risks at each decision point. The challenges, anticipated and unanticipated, will be more manageable in this way. If vehicles less than 1,000 tons GTOW are successful, they will serve as the technology demonstration and development stepping-stones to the very large scale, military lift concepts. The WMAT has concluded that there are several useful applications which require payload, weight, and size configurations in the 400 to 800 ton range. It is possible that all of these useful applications could be performed by wingship variants of a single basic design. Any continuing Mission Analysis effort should investigate this possibility with this stepping-stone sequence in mind.

8. Significant Technical Findings

There has been significant engineering, analysis, experimentation and design effort on WIG vehicles during the past 60 years. Investigators from many countries have contributed. The Russians, by far, have had the biggest programs and have designed, built and tested the largest vehicles. The current Russian program has been underway for about 30 years.

There have been no actual operational deployments of WIG vehicles.

The large Russian wingships are a significant technical achievement. They have lifted the largest weight ever (about 1.2 million pounds) from water.

The Russian programs focused on entirely different applications than current U.S. interest. They concentrated on tactical military short range missions--not on the strategic supply mission. They are rugged, heavy, military vehicles built by the shipbuilding community. The design legacy is from surface vehicles--not aircraft.

Several intrinsic deficiencies limit achievable wingship performance. The takeoff thrust requirements result in large engine weight and drag which penalizes the cruise portion of the mission and increases life cycle cost. The water impact loads even in relatively smooth water contribute to large structural weight fractions. The significant aerodynamic drag of required hydrodynamic features (steps, spray strips, etc.) and the required large horizontal stabilizer detract from the improved efficiency in ground effect.

Russian wingships are technologically primitive by western standards. Even with blowing under-the-wing for takeoff, the thrust required for takeoff is three to five times that required for cruise. Existing design are very inefficient during low-speed maneuvering. In cruising flight, they turn by banking as a conventional aircraft does. They use aviation engines with modifications to adapt them to the marine environment. All Russian craft have been experimental flight test articles or concept demonstrators.

Existing prediction methods are inadequate to address performance of under-the-wing blowing. Russian designers believe the scaled up design beyond a factor of three (about 2.5 million pounds based on their heaviest current design) would be <u>very</u> risky. The Russians see limited utility beyond this size.

Several available western technologies could improve the overall performance of wingships. Remote sensing and advanced navigation systems could help avoid obstacles and rough water and

optimize routing. "Intelligent" controls and digital systems may facilitate improved takeoff and landing performance. Advanced structural materials and concepts may improve the currently unimpressive structural weight fractions. Thrust augmentation of high-bypass-ratio engines may help mitigate the takeoff power problem.

9. Conclusions

Several military missions which emphasize the speed and persistence possible in wingships have been identified and appear promising. However, the completed phase of the missions analysis study has not fully evaluated the alternate applications for existing or projected (within 20 years) capabilities of wingships. Specifically, preliminary analyses have not shown a strategic heavy lift mission to be promising.[1]

The Russian programs have not resolved many issues that are fundamental to developing wingship with attractive range-payload performance. These issues remain either because they are too difficult or because the Russian program did not strive for competitive range-payload performance. They have demonstrated significant performance (in raw weight lifting) but they have not built many (more than 5) of any design. There is no evidence of operational capability.

Modern technologies have not been fully adapted to the wingship application. Some could improve performance. For example: (1) composite structures may reduce structural weight fraction; (2) digital flight controls may improve safety and permit greater design freedom; (3) advanced propulsion technology may improve efficiency and other performance measures. These technologies also improve the performance of conventional aircraft and ships.

Wingships approaching the efficiency and capacity required for strategic mobility are ten times larger (in gross weight) than any similar craft. Such wingships are about 5-times larger (in weight) than the experienced Russian or American design teams would pursue at this time. Adequate propulsion concepts for these very large wingships do not presently exist, and there are no current plans to develop wingship-specific propulsion concepts.

[1]There is considerable divergence of opinion on the potential utility of the 5000-ton class wingship for strategic mobility. Uncertainties contributing to these divergent opinions are: (1) affordability; (2) infrastructure impact; and (3) relative competitive advantage over alternatives. A minority report on the utility of the 5000-ton class Wingship is included in Appendix M. There is also considerable divergence of opinion on the commercial potential of wingships of all sizes. Uncertainties contributing to these divergent opinions are: (1) affordability; and (2) whether it is more practical to design for broad market applications (the aircraft approach) or the design for specific routes (the ferryboat approach).

10. Taxonomies Of Technology And Concept Demonstrators

In facing the complexities associated with technology, the technology base and the status of the "wingship," it may be useful for the purpose of discussion to over simplify the relation between two classes of "demonstrators." One of these is a so-called "Technology Demonstrator" and the other is a so-called "Concept Demonstrator." The former answers a simple question namely, "Will the idea work?," or "Is the idea feasible?," while the latter is directly related to the first step of development of a new product. Understanding the basis for a "Technology Demonstrator" requires some discussion of our "technology base." Again over simplification helps the explanation of what is really not an orderly process. The "technology base" is really a collection of information. The collection is very broad indeed, encompassing the entire universe of technical knowledge. In given circumstances the breadth is much less imposing, but is never the less very broad.

The origin of this information is equally catholic. One normally thinks of this information as flowing either directly from scientific knowledge, or from knowledge that is the out-put of applied science (i.e. the application of scientific principles and knowledge to new situations). Actually the sources are much more diverse and include information from the field on current products, both in-house and from the competing products; from design studies of potential products; from construction of analogies and from inventors. This is shown in Figure 10-1. Of course there is a continual feedback process. Thus some applied science is stimulated on results generated in the technology base as is some science.

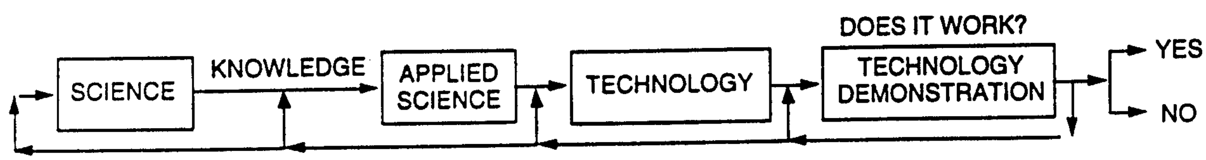

Figure 10-1
A Simplified Taxonomy of "Technology Demonstrators"

The central point is that whether or not a "Technology Demonstrator" is constructed to answer the question is "Will the idea work?". The "Technology Demonstrator" demonstrates a proof of principle. It is not usually central to product development, even through the people constructing the "Technology Demonstrator" may well have a product in mind and in practice often do. In the DoD budget line, a "Technology Demonstrator" belongs in the 6.2 budget line. There is no program associated directly with the demonstration, although if the "Technology Demonstrator" answers the "Will it work?" question as yes, some further steps may happen. To follow this further we need to show the corresponding flow of information related to product development (Figure 10-1).

This report shows that the Russians have completed a technology demonstration on a 540 ton machine, the so-called "Caspian Sea Monster" (CSM). The report shows that the phenomena encountered by a trans-oceanic transportation system, of which the "wingship" is an essential feature, favor a very large sized machine.

The report also shows that there are essential technology elements, that have yet to be demonstrated on any scale larger than the CSM such that a scale-up of a factor of 10 in weight (2.15 in length) is a very high risk, (and that the costs associated with the scale-up will also be of the order of billions of dollars). In short, a technology base is not yet available to support a "Concept Demonstrator" of a size needed.

The basis for this conclusion is illustrated by the following line of reasoning. Preliminary design studies suggest that the sum of fuel weight plus the payload weight for a competitive wingship must be around 65% of the maximum design gross weight. For current aircraft design (i.e. 747 which weighs about 800,000 pounds) this ratio is about 50%.

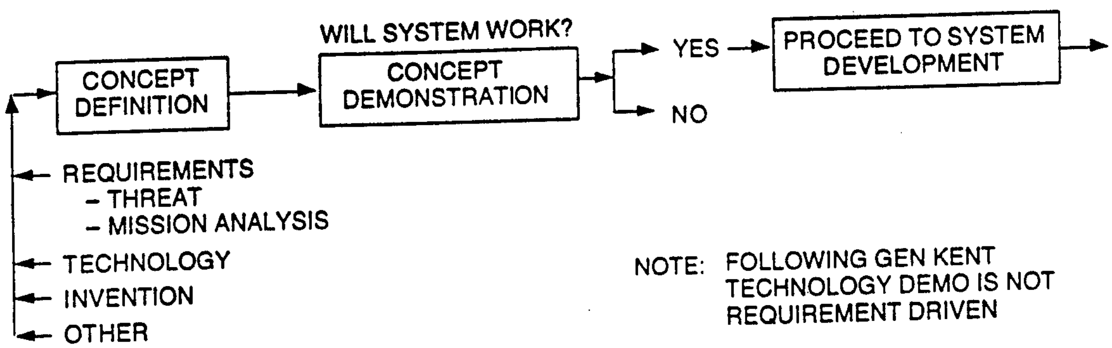

Figure 10-2
Product Taxonomy

Advances in material suggest that if the 747 were to be designed now, the ratio would be about 50%. However, the difference between an 800,000 pound machine and a 10,000,000 pound machine are such that it is not clear the technology base exists to support the design of a wing-carry-through-structure of modern light weight materials. Hence it is appropriate to consider a sequence of "Technology Demonstrators" whose purpose is to show, for example, suitable full sized wing-carry-through-structures can be built for machines of 1.5 million, 3 million, 6 million and 9 million pounds to provide a technology base to ensure a light weight structure can be built for a 10 million pound "wingship". Naturally it would be necessary to build a "Concept Demonstrator" to verify the actual design for a real vehicle of that size.

This report also shows that the Russians have made the attempts at concept demonstrators (the ORLYONOK and the LUN) and neither of these concepts became operational. The reason for these craft not becoming operational may be either as a result of concept deficiencies or the general conditions in the FSU. To determine whether or not the wingships of currently practical sizes can be of significant value to the DoD requires completing the study of missions and applications.

11. RECOMMENDATIONS

Based on the content of and conclusions reached in this report, the ARPA Program Manager makes the following recommendations:

1. **Recommend completing the mission and utility analyses.** This effort should be further broadened to include missions other than long range heavy lift. It should consider the possibility of dual-use (military and commercial) technology and craft designs. The analysis must involve potential user communities and assess cost effectiveness. The design and technical feasibility of the wingship is strongly dependent on the types of missions it is required to perform. The Wingship Mission Analysis Team has looked at a wide variety of missions that could be performed by wingships. A number of promising military and commercial missions have resulted from this effort.

2. **Recommend a preliminary design study** to determine the physical characteristics of the wingship and related potential vehicle configurations which could perform these missions. Vehicles which are true hybrid craft - having a sea sitting capability approaching that of Russian-style wingships, but with an altitude capability more characteristic of seaplanes - should receive consideration. More detailed cost and effectiveness analyses of these configurations would (1) reduce the uncertainty inherent in the current assessment, (2) provide a more accurate characterization of the wingship's potential as an operational vehicle, and (3) provide guidance for planning relevant technology development.

3. **Recommend that a technology development program** focused on key technical issues associated with a selected wingship concept be implemented. This effort should be sponsored by an eventual wingship user. Major deficiency areas such as wingship specific propulsion and structures must be given the highest priority. Consideration should be given to involving Russian expertise in relevant areas such as advanced design and hydrodynamics. Resolution of these and other issues, and the attainment of solutions to known technical problems are viewed as prerequisite to further design and development activities associated with larger wingships. The technology roadmap developed by the technical evaluation team should be used for guidance in this effort.

4. **Recommend completing ongoing studies** to address the very most important wingship-specific propulsion problems such as the large power required for takeoff.